Session 11, S11

Plasma-based UTA Emission in BEUV & Water Window Spectral Regions

Takeshi Higashiguchi[1]

Takamitsu Otsuka[1], Weihua Jiang[2], Akira Endo[3], Thomas Cummins[4], Colm O'Gorman[4], Bowen Li[4], Deirdre Kilbane[4], Padraig Dunne[4], and Gerry O'Sullivan[4]

[1]Utsunomiya University
[2]Nagaoka University of Technology
[3]HiLASE Project, Institute of Physics AS, Czech Republic
[4]University College Dublin (UCD)

2012 International Workshop on EUV and Soft X-Ray Sources
October 11th, 2012, UCD, Dublin, Ireland

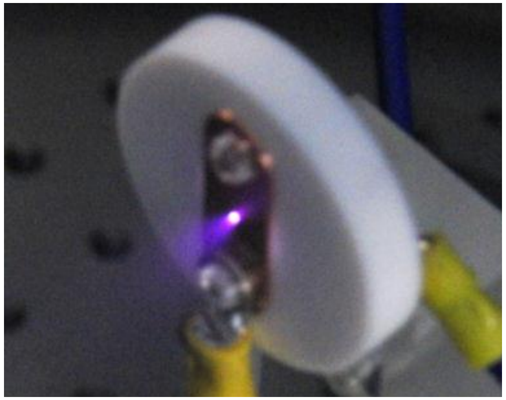
HW for very near future

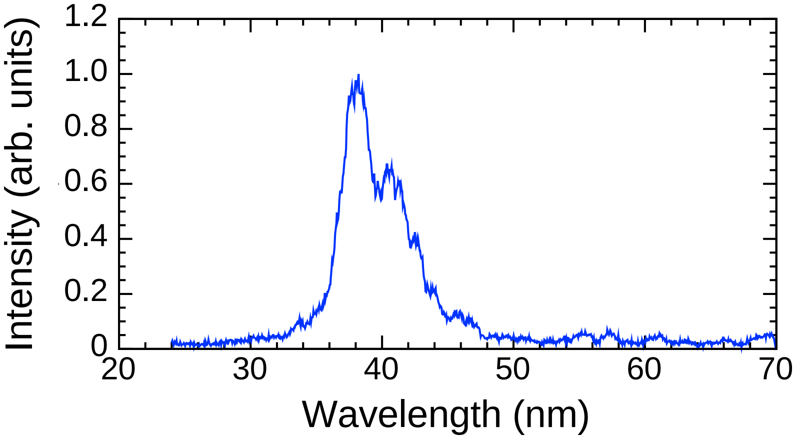
- HVM source at 13.5 nm
- Compact brightness source at 13.5 nm
- BEUV source at 6.X nm

In order to understand the wavelength scaling from EUV to water window SXR.

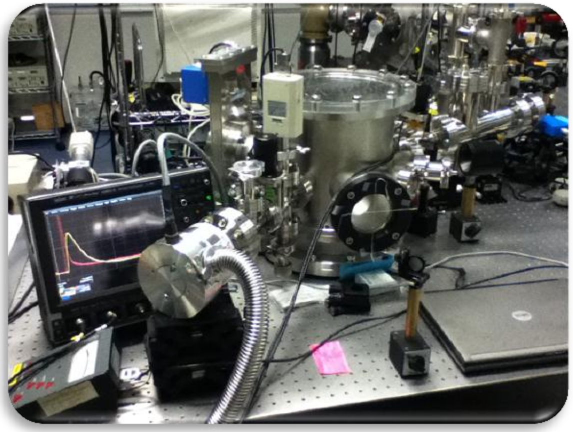
XUV & EUV sources

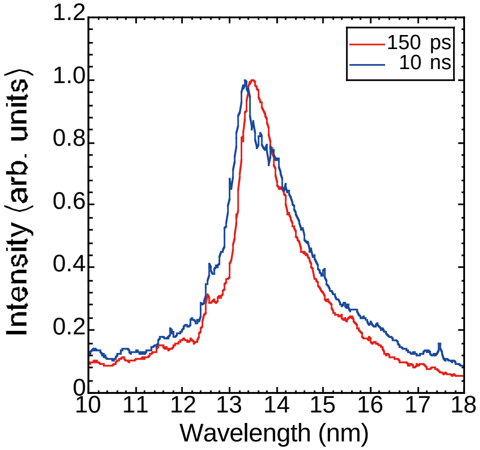
- Compact discharge 40-nm source

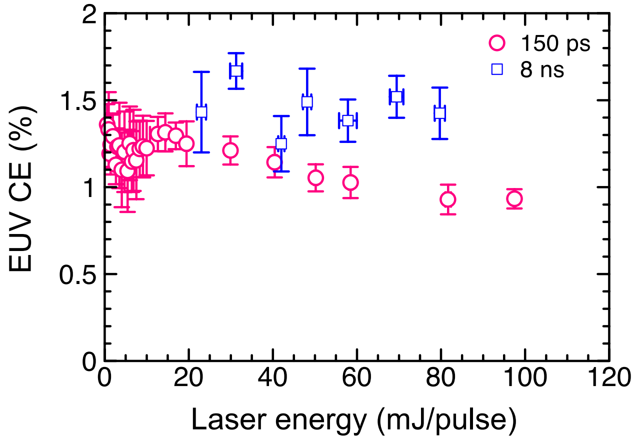




- 13.5-nm high brightness sources

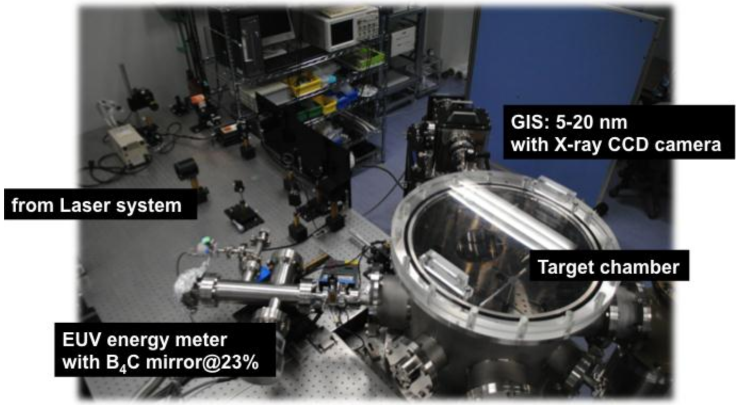


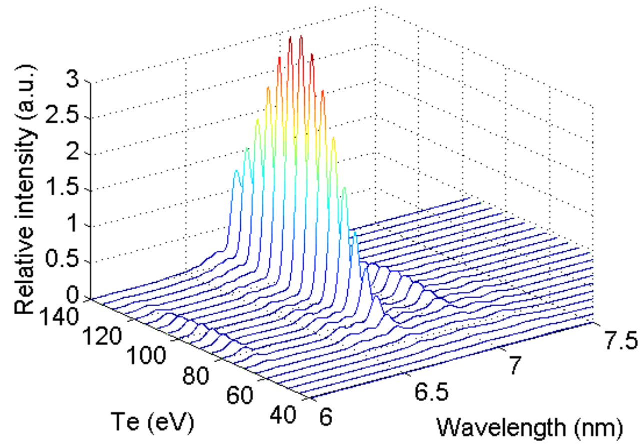




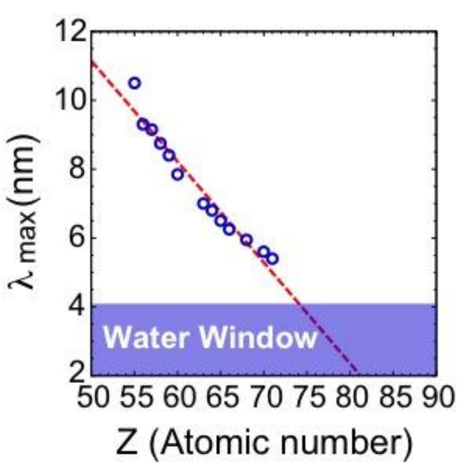
BEUV & WW-SXR sources

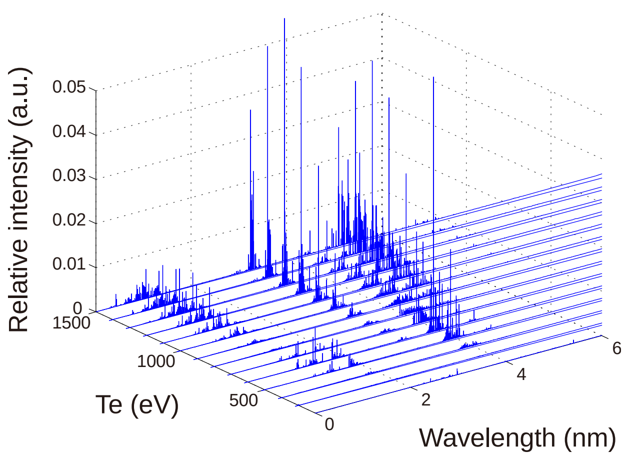
- BEUV sources at 6.X nm

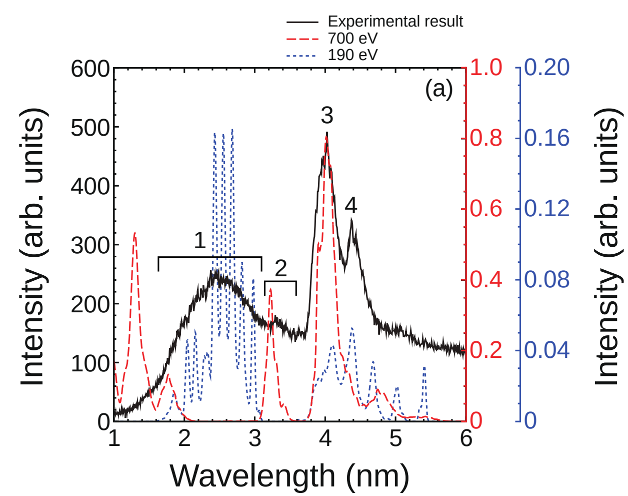




- Water window SXR sources







Why 6.X nm EUV source?
Beyond EUV (BEUV) source

From Banine presentation shows as follows:

(1) extensive (beyond 8 nm@~2017)

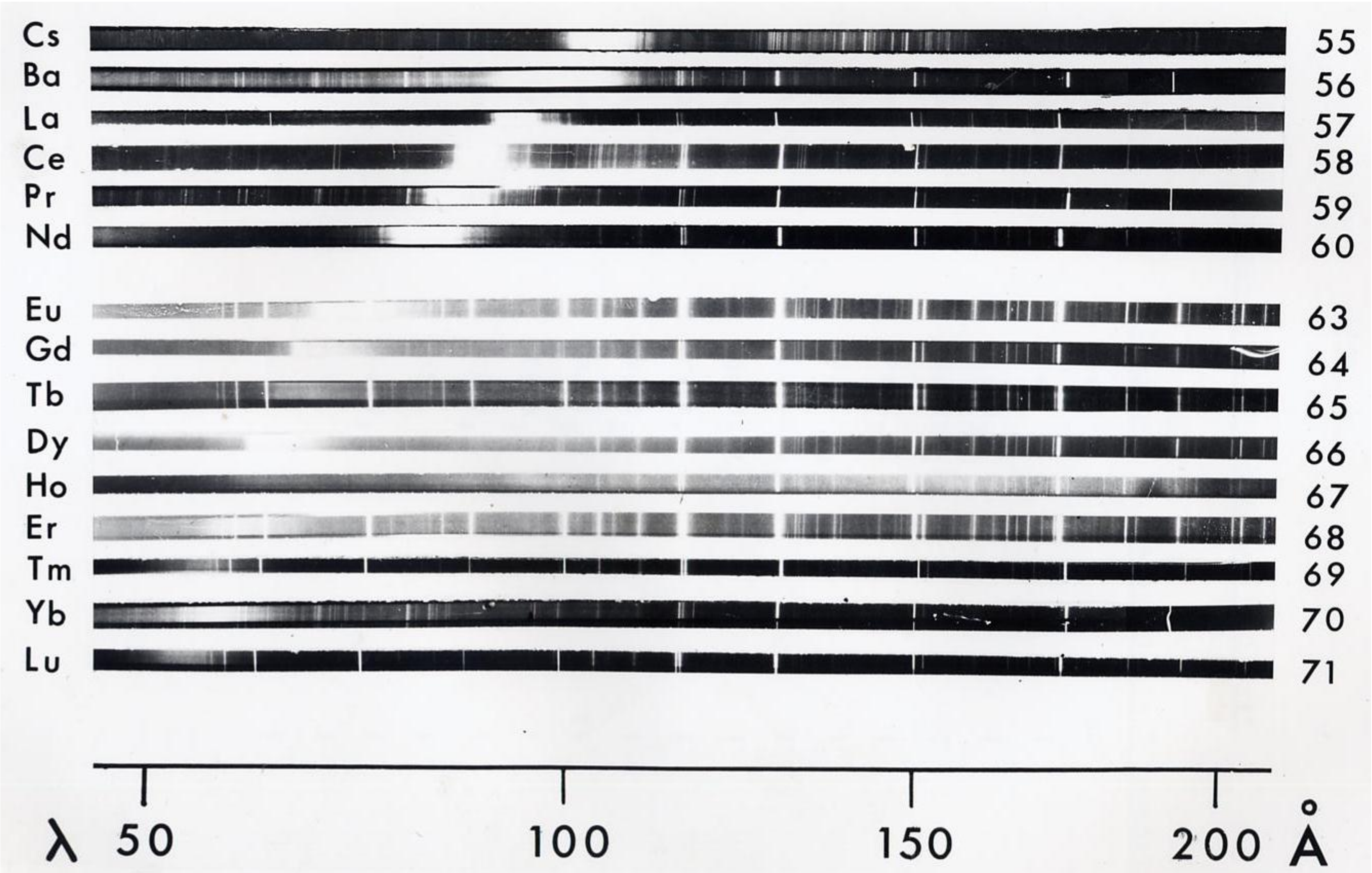
(2) 6.X nm choice: Best transmission & Easier Manufacturing

(3) Source: New fuel is needed (Gd and/or Tb, other???)

(4) *R* ~ 80% (cal), *R* ~ 40% (exp)@La/B_4C MLM

(5) *Optical throughput for 6.7 nm & 13.5 nm is comparable!!!*

Another material plasmas
UTA emission from high-Z plasma



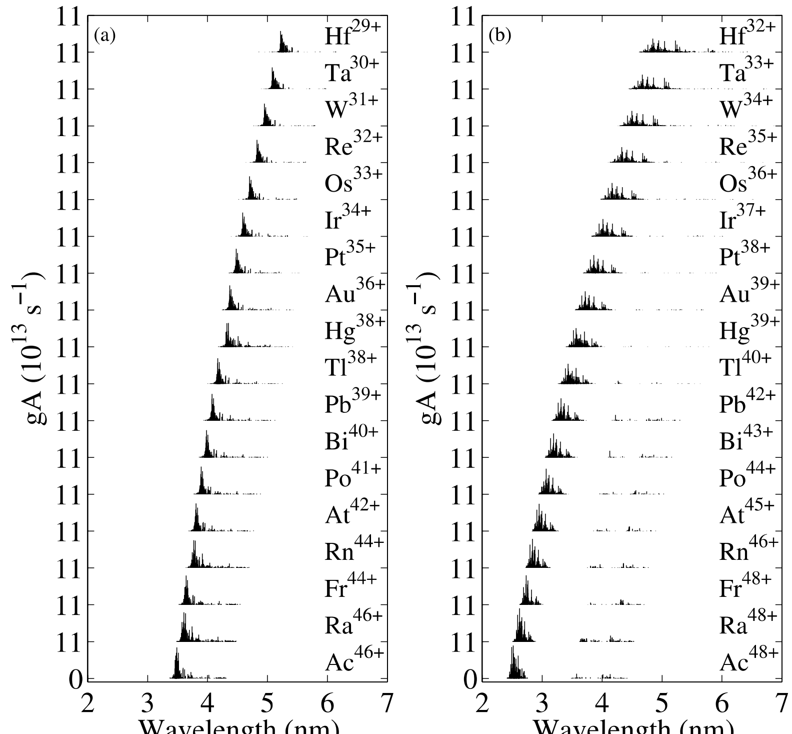
Various target emissions

IOP PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

J. Phys. B: At. Mol. Opt. Phys. **44** (2011) 165006 (9pp) doi:10.1088/0953-4075/44/16/165006

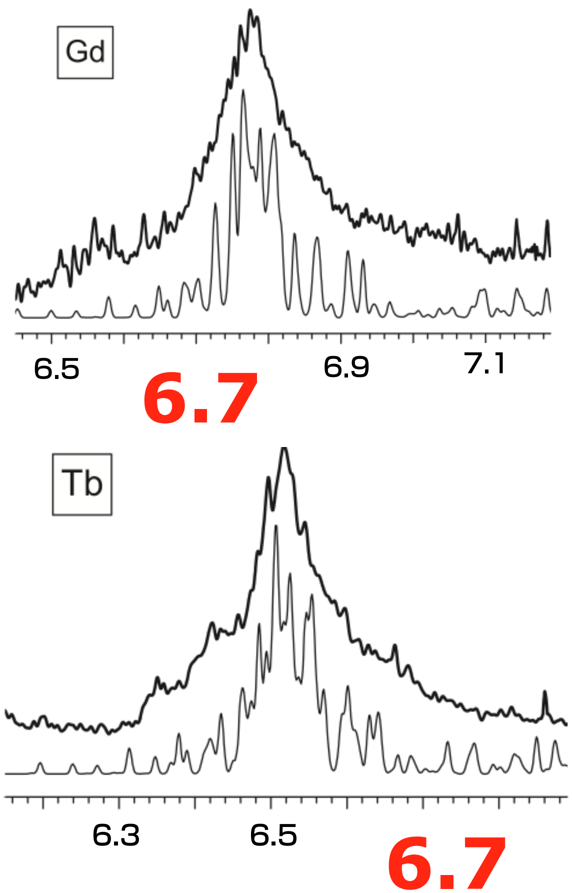
Transition wavelengths and unresolved transition array statistics of ions with Z = 72–89

D Kilbane

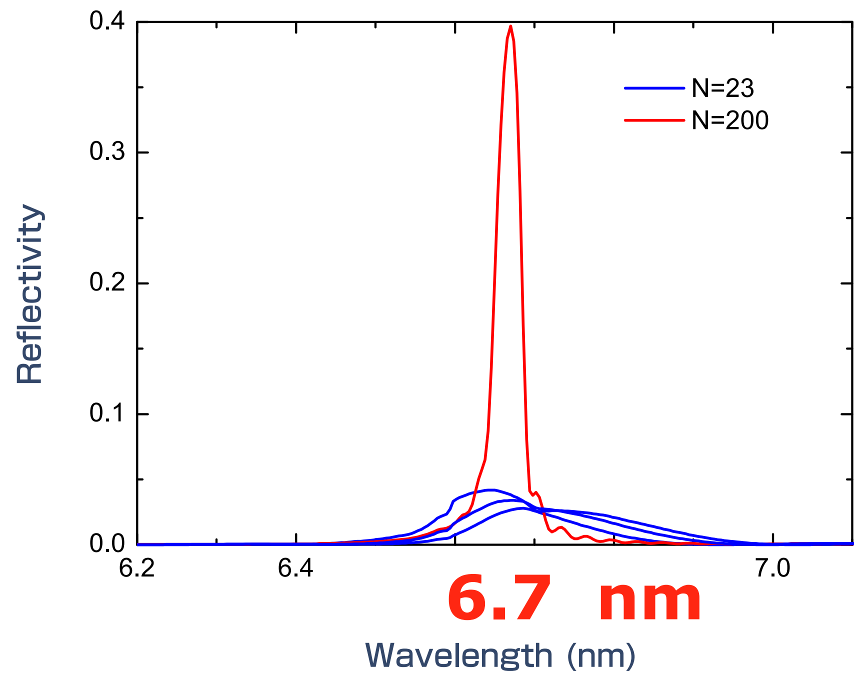


Introduction…
from previous presentation

6.7 nm: Gd, Tb plasmas



Mo/B_4C mirror

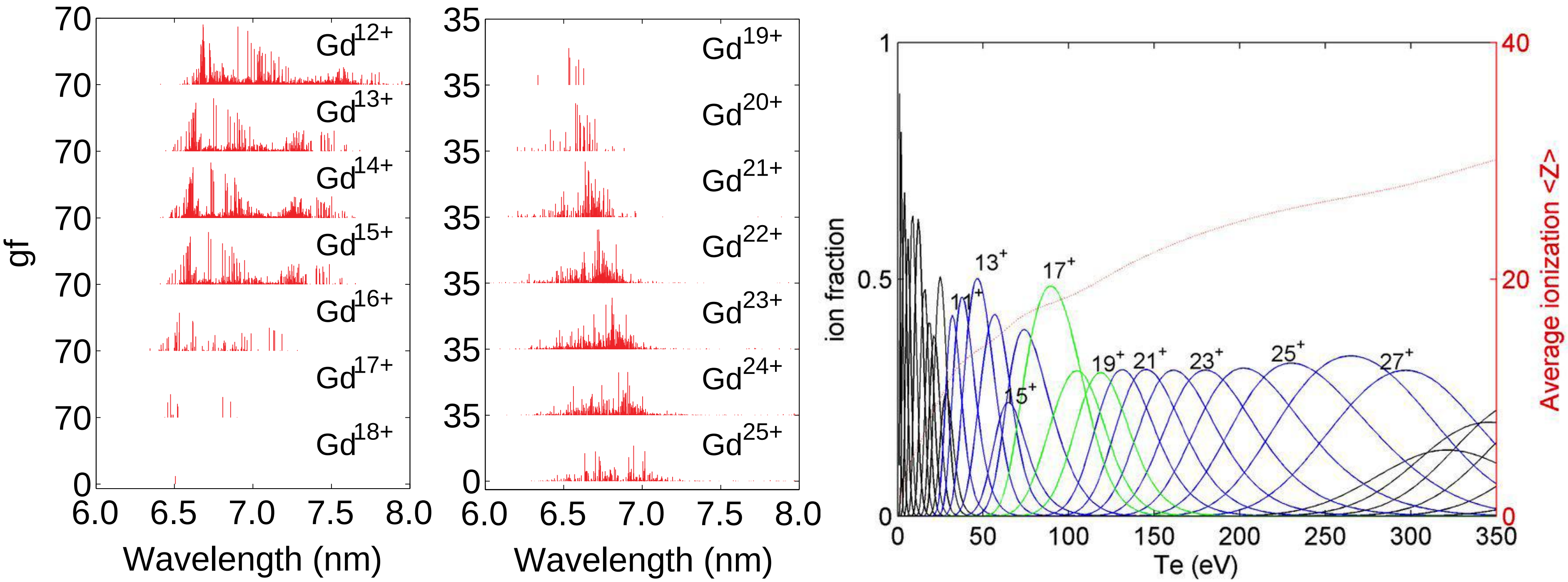


Fraunhofer IOF

S. S. Churilov *et al*., Phys. Scr. **80**, 045303 (2009).

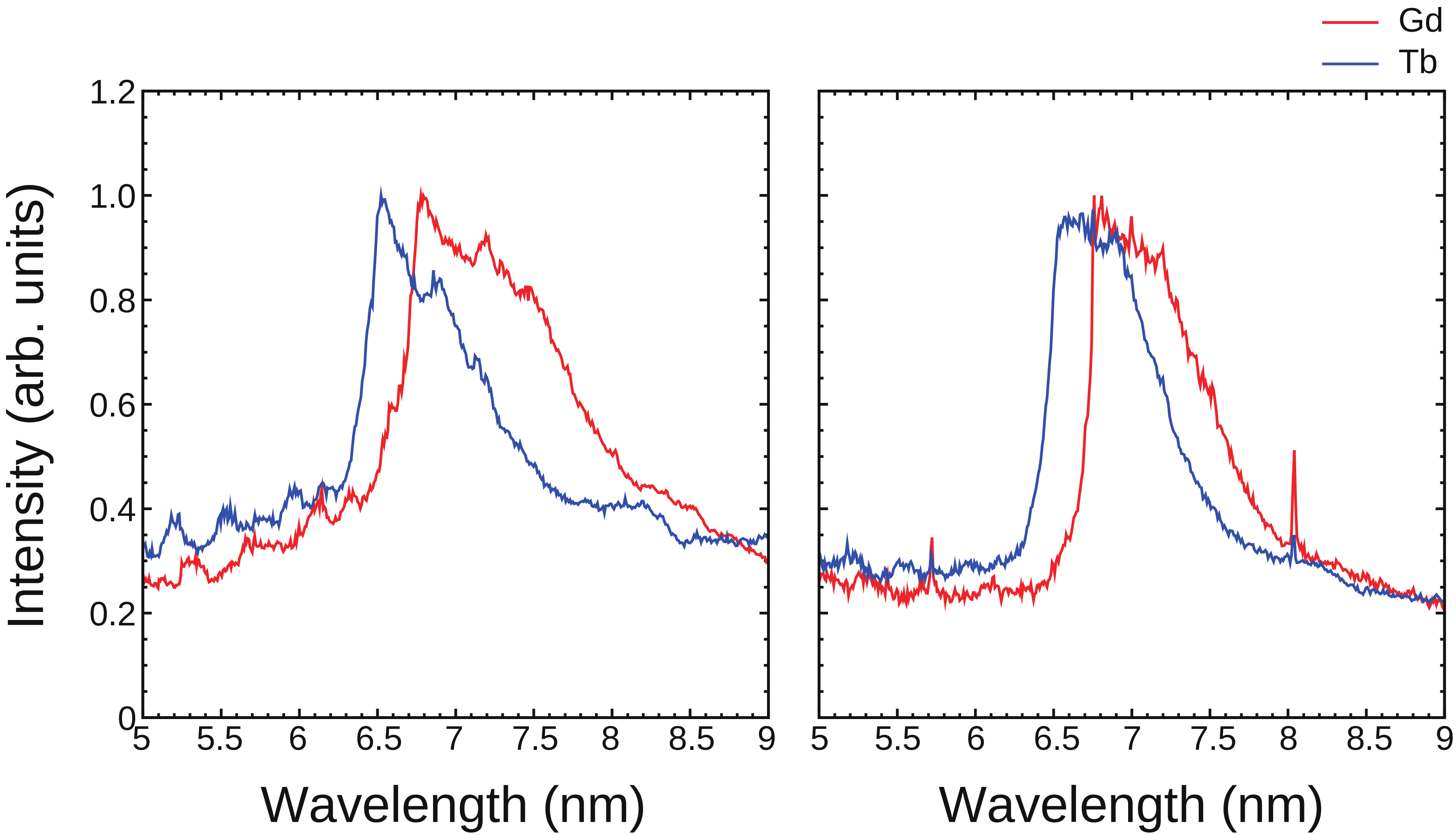
gf spectra & ionic population

We confirm the UTA resonant lines around 6.7 nm



T. Otsuka *et al*., Appl. Phys. Lett. **97**, 111503 (2010).
B. Li *et al*. Appl. Phys. Lett. **99**, 231502 (2010).

Gd and/or Tb plasmas for 6.X nm

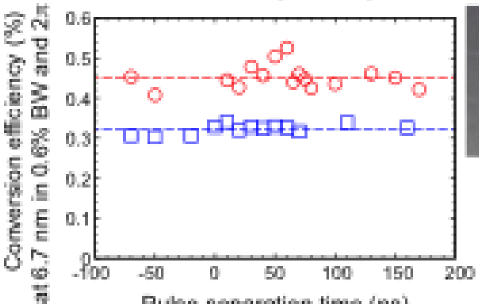


Feasibility study for 6.X-nm sources

$$I(\lambda) = I_0(\lambda)e^{-\sigma n \ell}$$

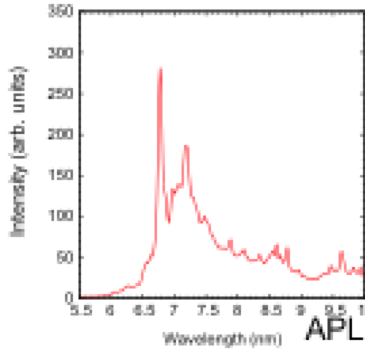
Feasibility study for 6.X-nm sources

low density target



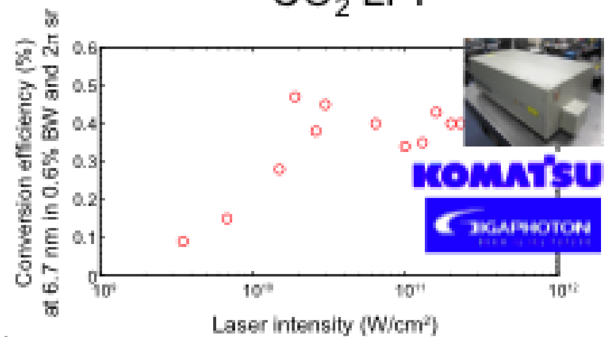
APL **99**, 191502 (2011).

DPP



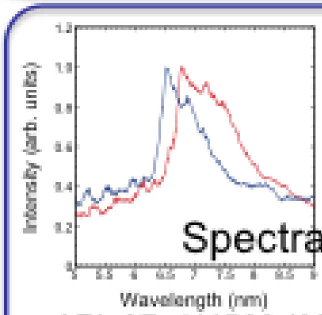
APL **99**, 231502 (2010).

CO_2 LPP



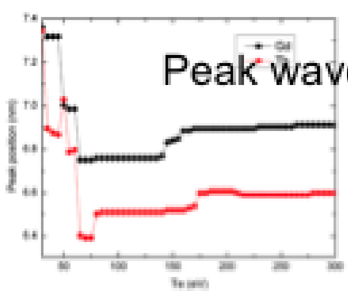
$$I(\lambda) = I_0(\lambda)e^{-\sigma n \ell}$$

$$\ell \approx c_S \tau_L$$



Spectral structure

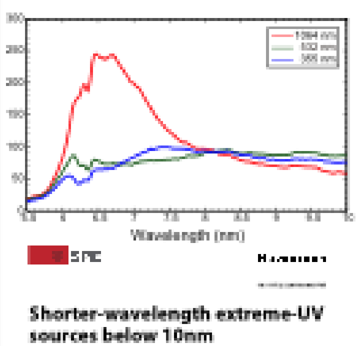
APL **97**, 111503 (2010).



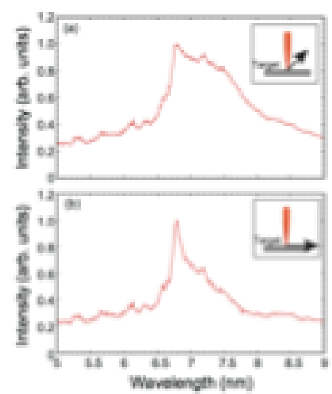
Peak wavelength

APL **101**, 013112 (2012).

Self-absorption

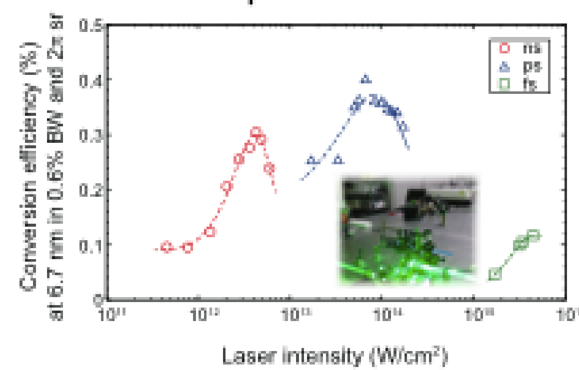


APL **97**, 231503 (2010).



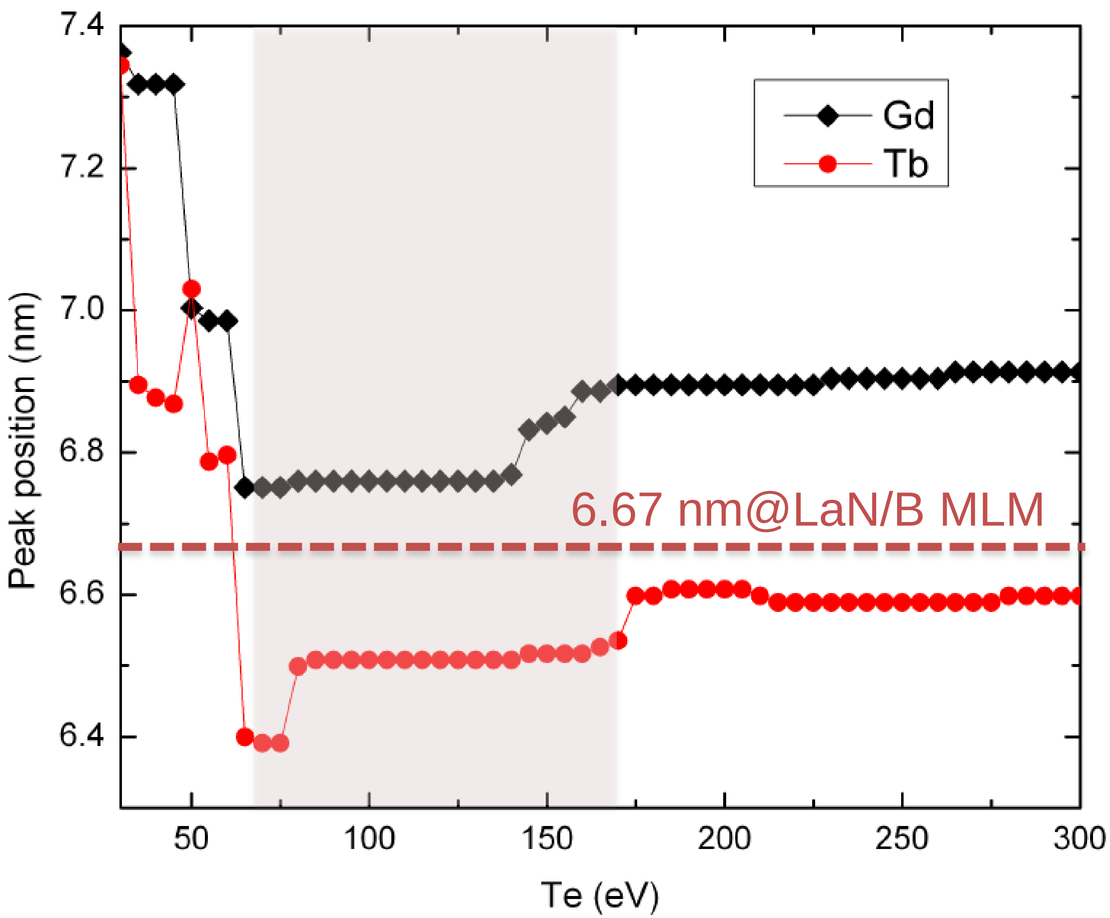
APL **100**, 141108 (2012).

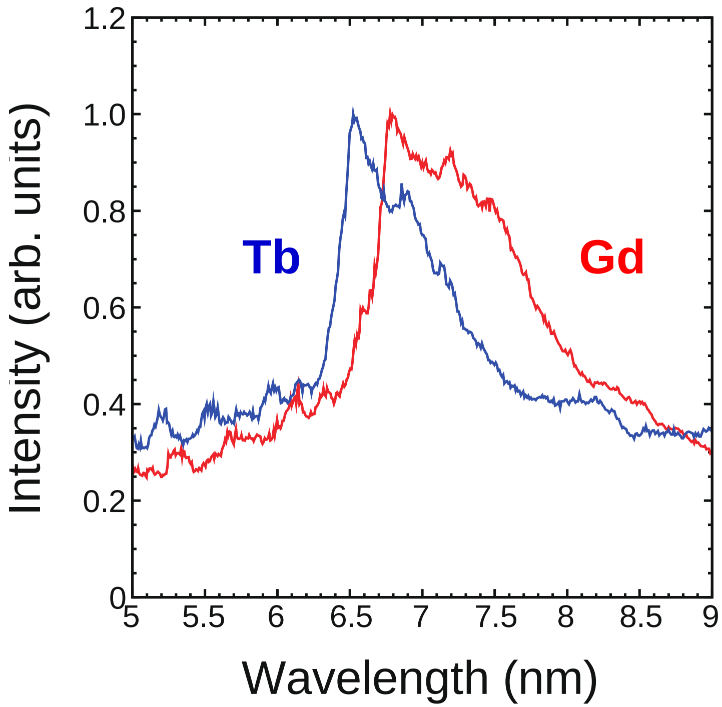
ps LPP



APL **100**, 061118 (2012).

Which wavelengths at 6.X nm?

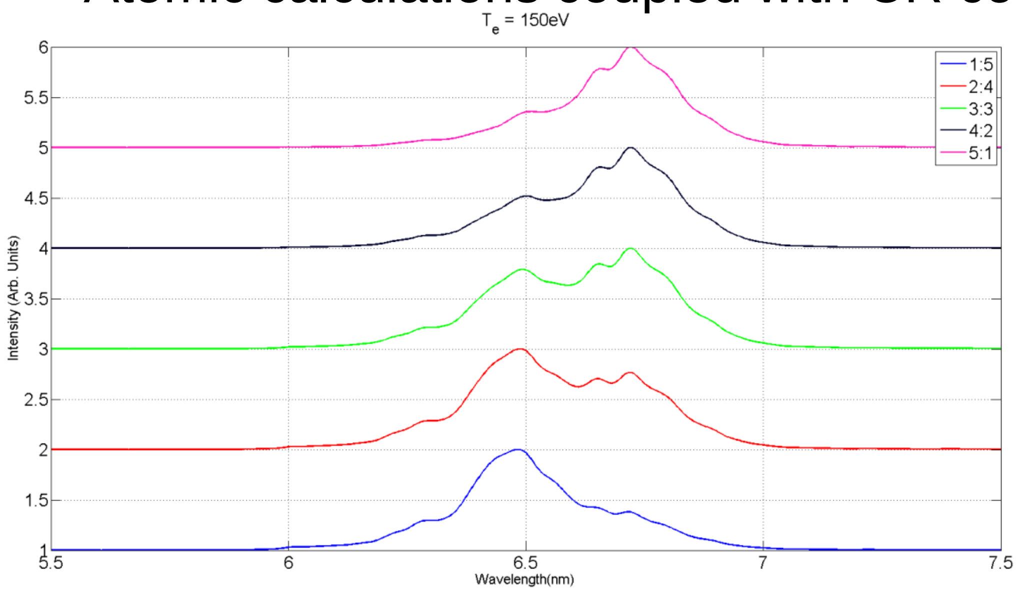




B. Li *et al*. Appl. Phys. Lett. **101**, 013112 (2012).

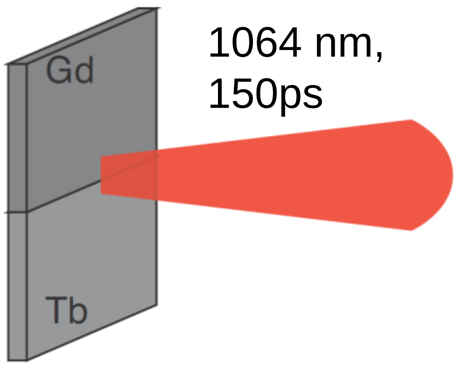
Complex target (proposal, preliminary)

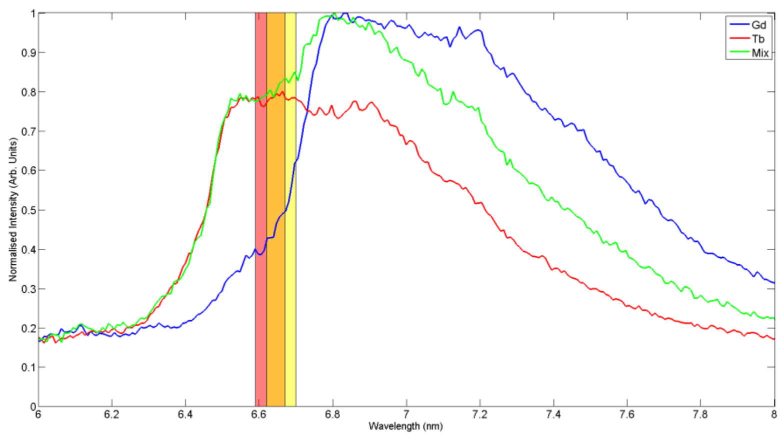
- Max MLM reflectivity peak lies between the peaks of Gd and Tb
  - Bowen *et al*., APL **101**, 013112 (2012)
- Gd – 6.76 nm $LaNB_4C$ – 6.66 nm
- Tb – 6.5 nm   LaNB – 6.63 nm
- Gd/Tb mix plasma could yield higher in band emission
- Wavelength "Tuning" may be possible
- Atomic calculations coupled with CR code

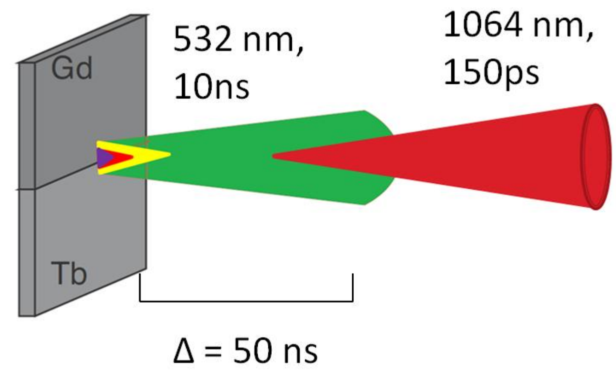


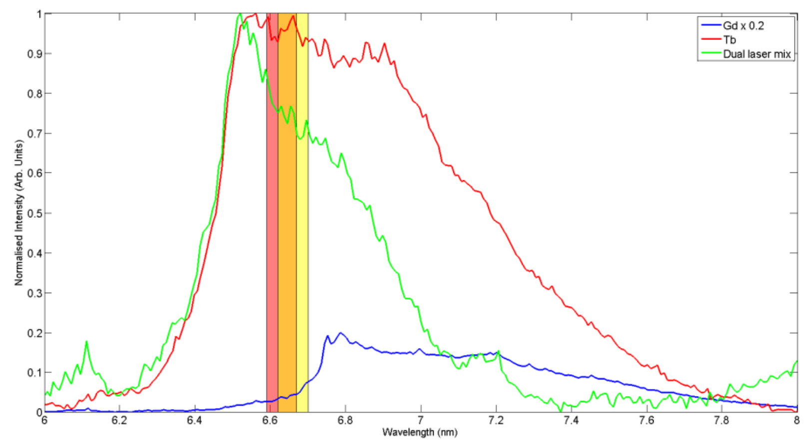
O' Gorman *et al*. – in preparation

Solid complex target







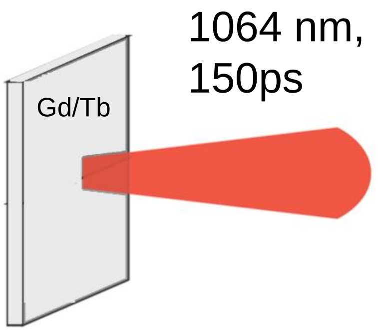


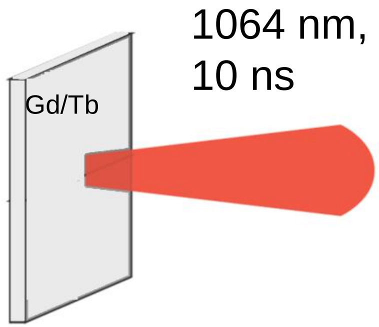
- T =150 ps
- Spectral profile shows higher in band emission

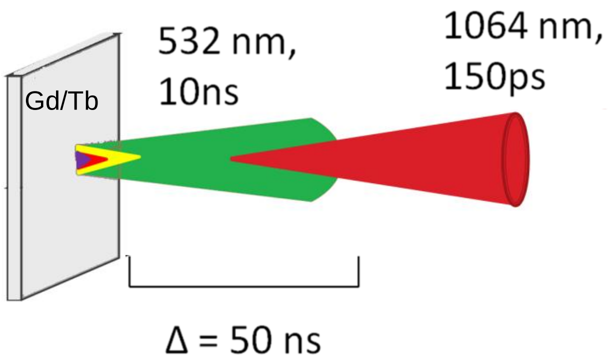
- Dual laser plasma
- Higher temperature and more absorption
- Emission has higher spectral purity than Gd & Tb

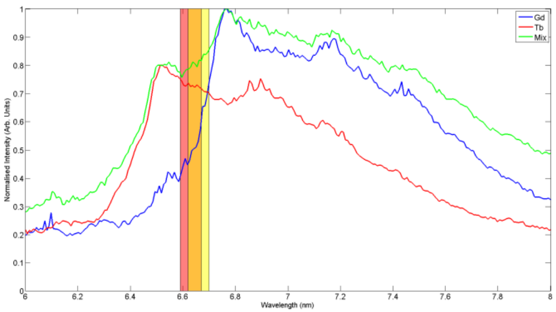
Low-density complex target

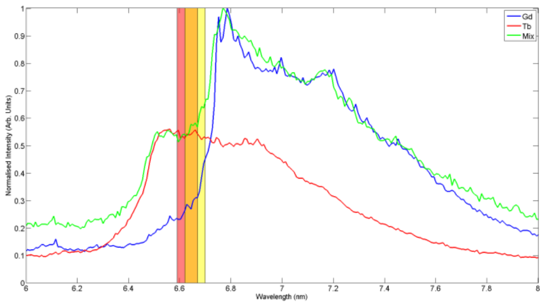
- Form Gd/Tb Target with 30% initial density
- Similar results with reduced absorption

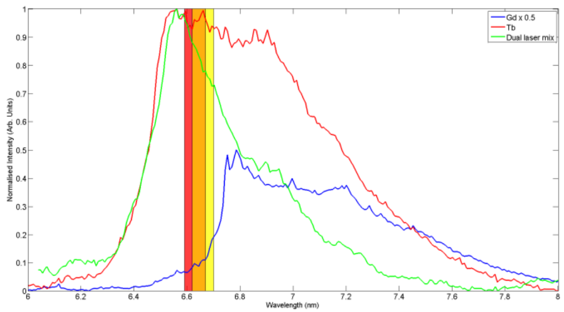




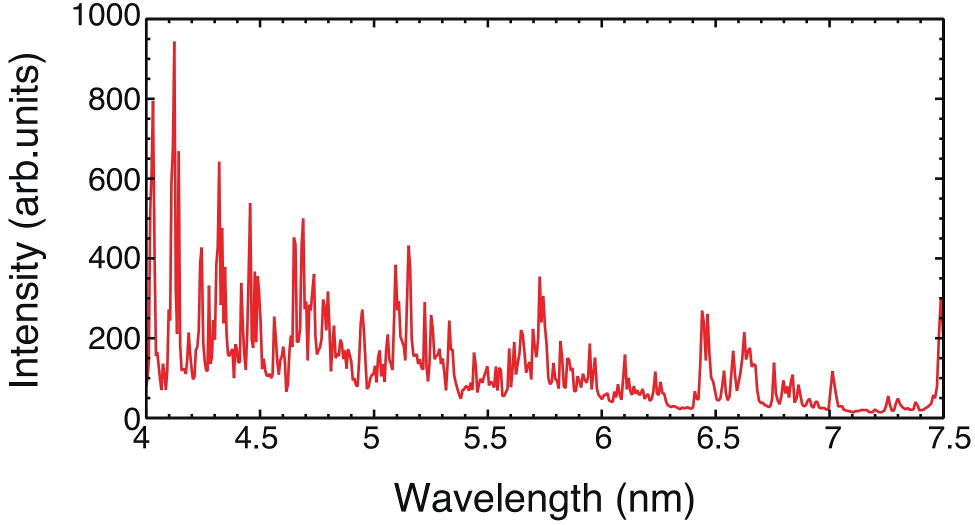


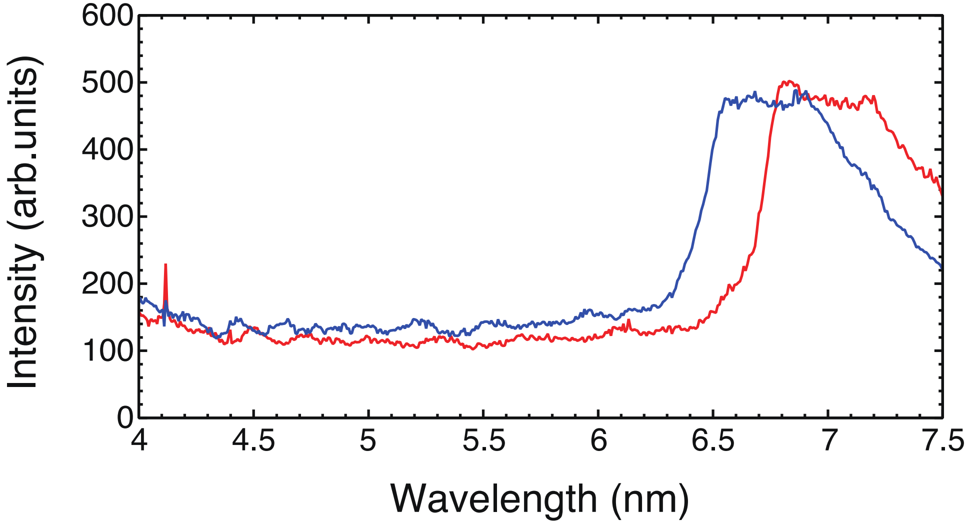


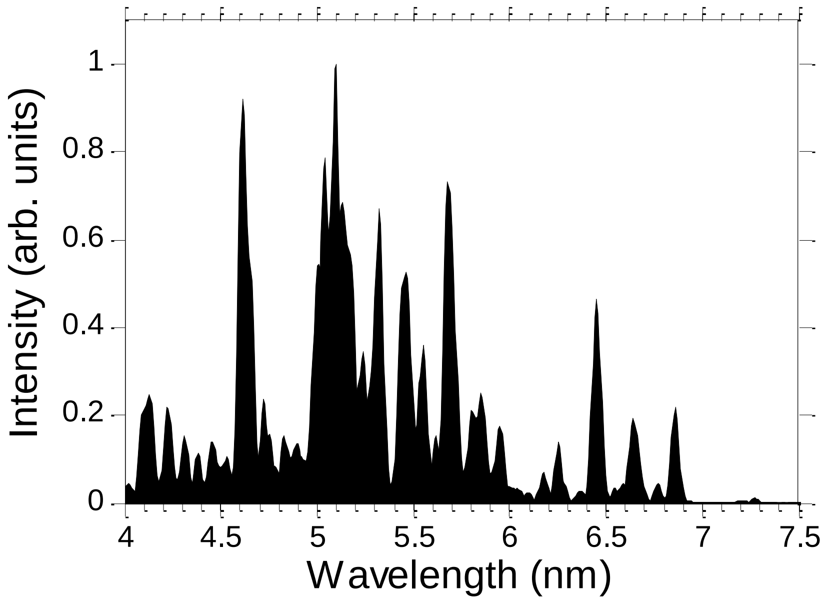




Other plasma: Phosphorus

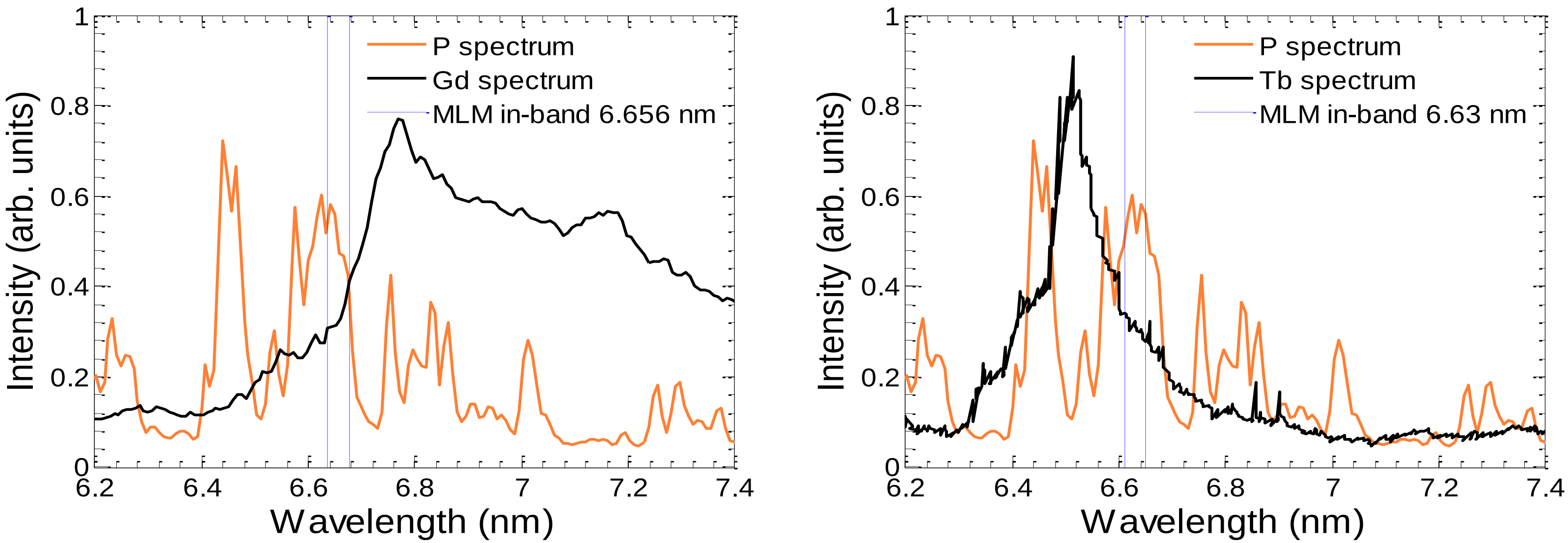






Line emission from Phosphorus plasma

- Phosphorus spectra observed using 10 ns Nd:YAG laser, ϕ = 7x10^{11} W/cm^2
- Line emission observed in 6.5-6.8 nm region due to $2p^5 - 2p^4 3d$ transitions of P^{6+} and $2p^4 - 2p^3 3s$ transitions of P^{7+} ions
- Wavelength of line emission appears better matched to in-band of MLM than Gd and Tb UTA



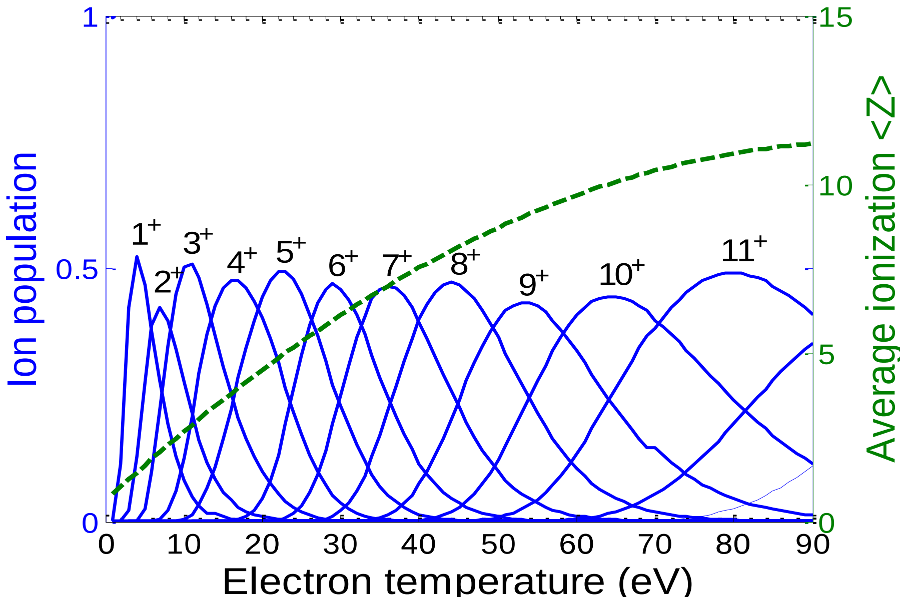
T. Cummins et al. (In preparation)

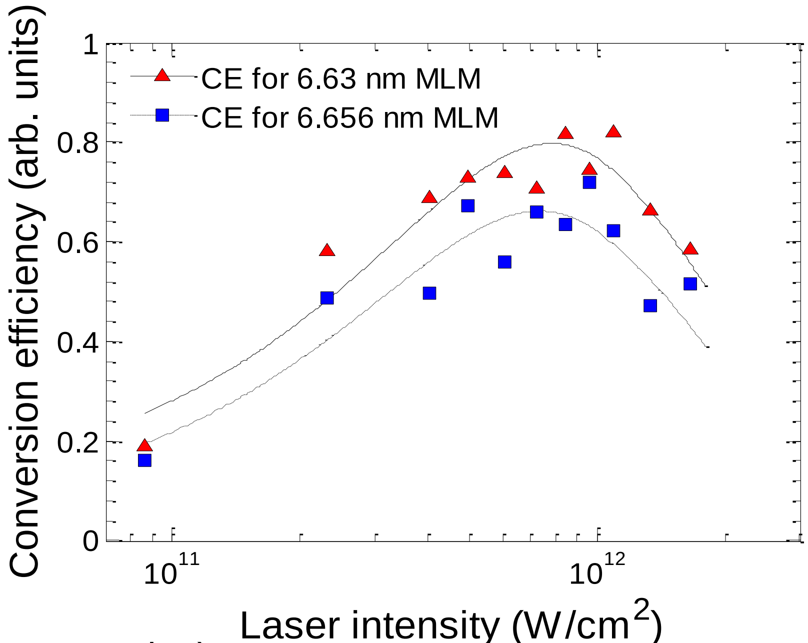
* Gd spectrum taken from C. O'Gorman *et al* Appl. Phys. Lett. **100**, 141108 (2012)

* Tb spectrum taken from S. S. Churilov *et al* Phys. Scr. **80** (2009)

Line emission from Phosphorus plasma

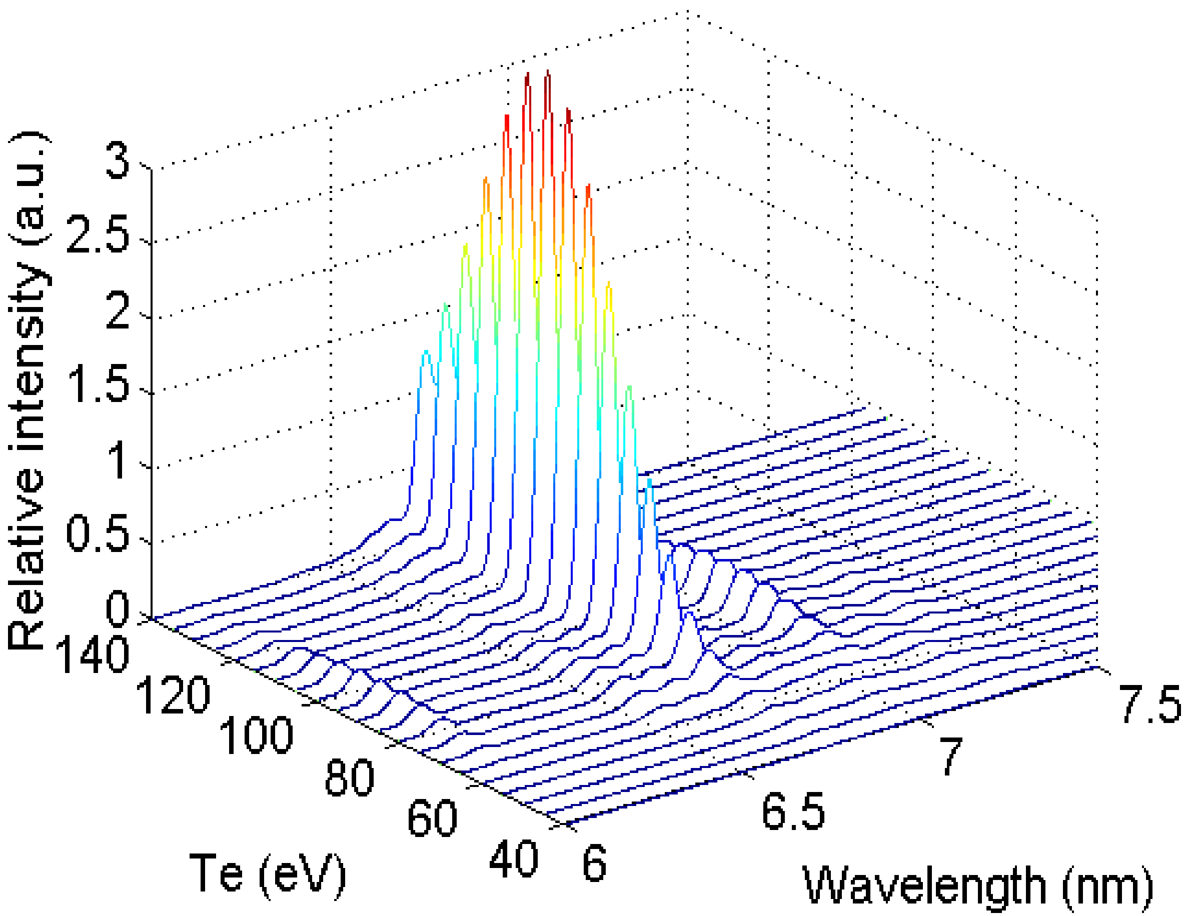
- FLYCHK code calculates ion population states and average ionization as a function of electron temperature
- Optimum electron temperature to achieve P^{6+}-P^{7+} is around 30 eV, comparable to existing requirement for Sn, and lower than > 140 eV for Gd and Tb
- Normalised in-band measurements show peak emission at around 7×10^{11} W/cm^2





T. Cummins et al. (In preparation)

Optimum electron temperature: 110 eV



CO_2 laser intensity:

2.4×10^{11} W/cm^2

B. Li *et al*. Appl. Phys. Lett. **99**, 231502 (2010).

Development of hybrid laser

- CO_2 laser-produced plasma behavior?
  - Low density, high temperature plasma

- Etendue
  - Expanding plasma size depends on temperature
  - Incident angle to 0.6%BW MLM at 6.X nm
  - etc…

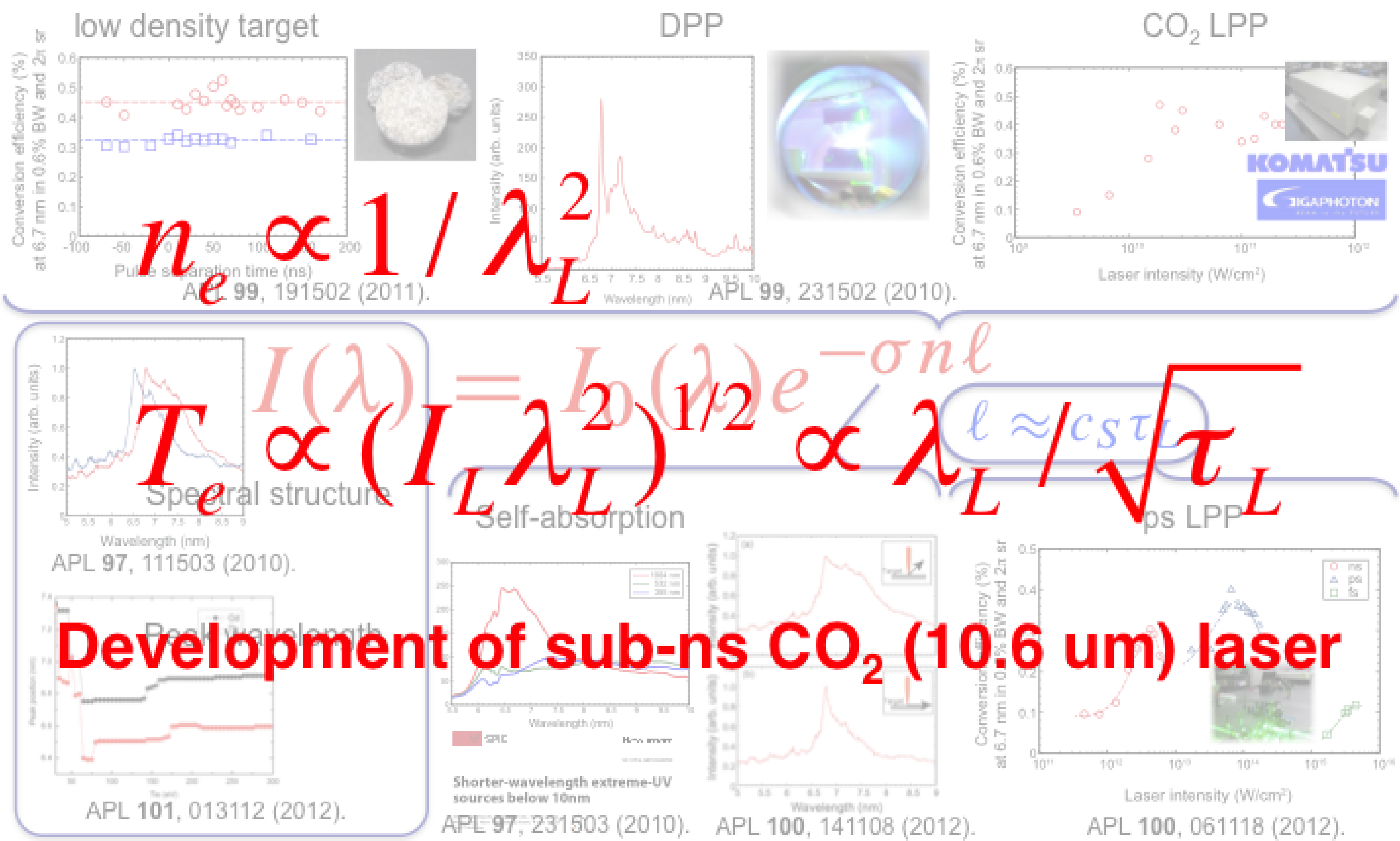
Low density & 100-eV plasmas

$$n_e \propto 1/\lambda_L^2$$

$$T_e \propto (I_L \lambda_L^2)^{1/2} \propto \lambda_L / \sqrt{\tau_L}$$

$$I(\lambda) = I_0(\lambda) e^{-\sigma n \ell}$$

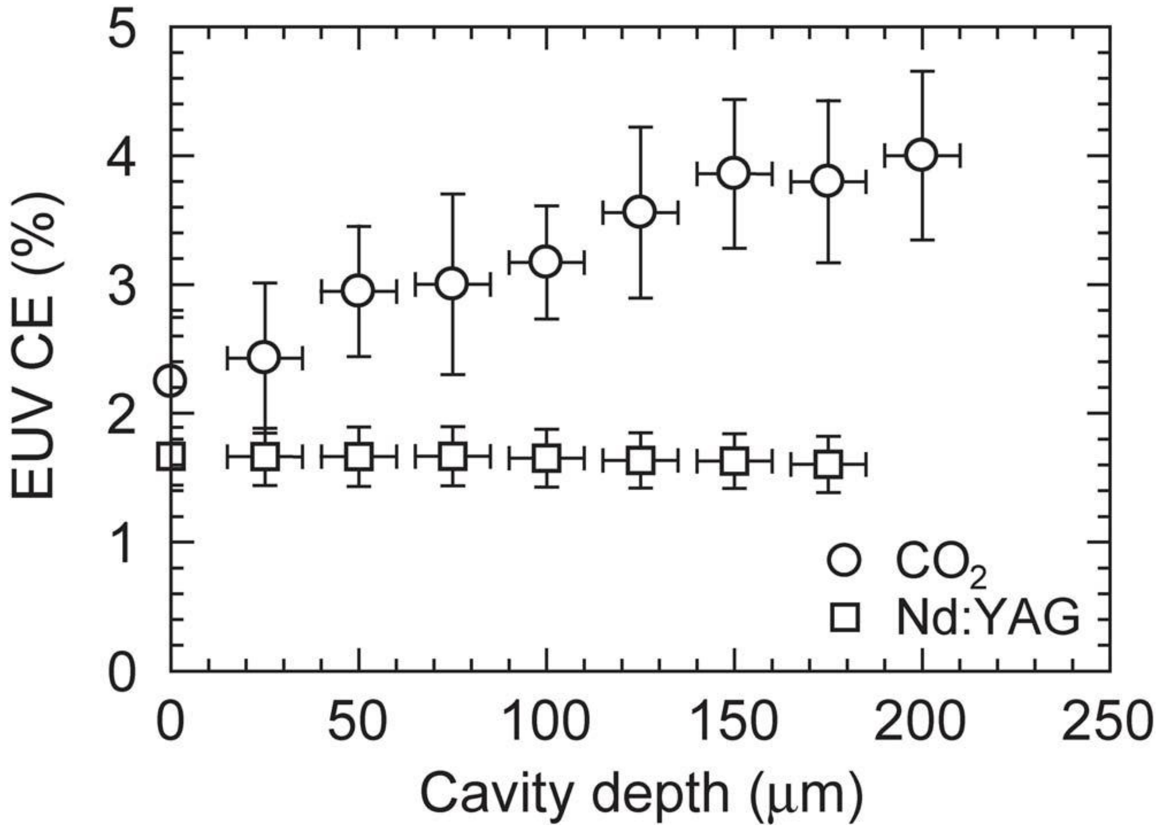
$$\ell \approx c_s \tau_L$$



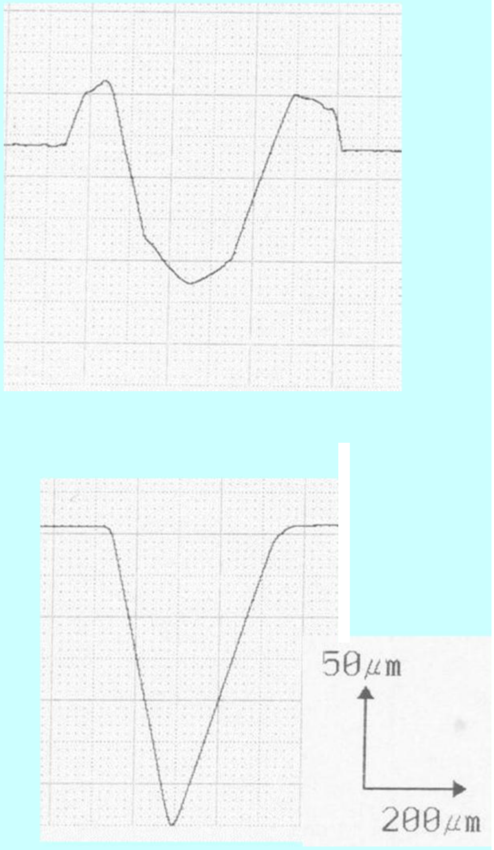
Development of sub-ns CO_2 (10.6 um) laser

CO_2 laser-produced Sn plasma

CE is expected to be 1.5% at the bandwidth of 0.6% for 6.X-nm BEUV.

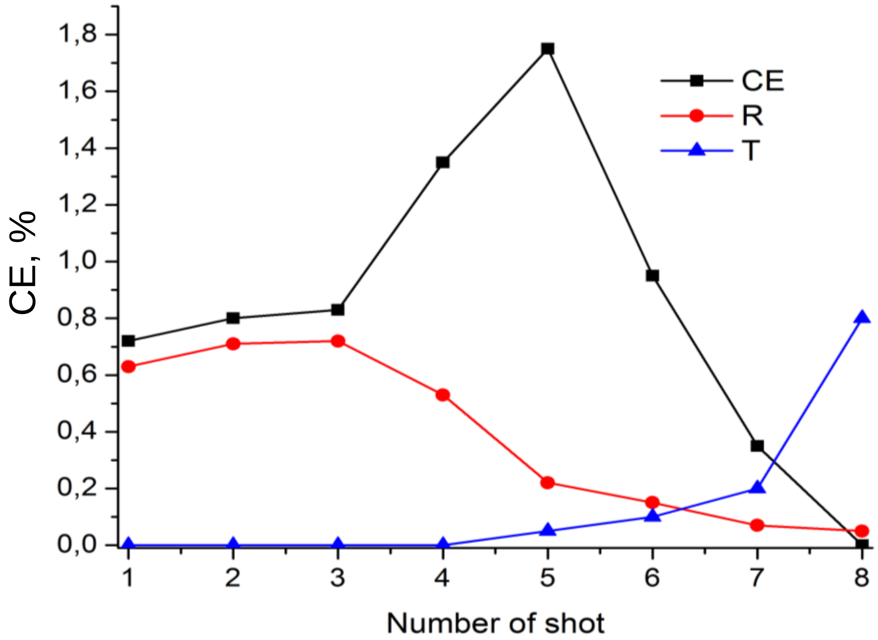


Cavity structure



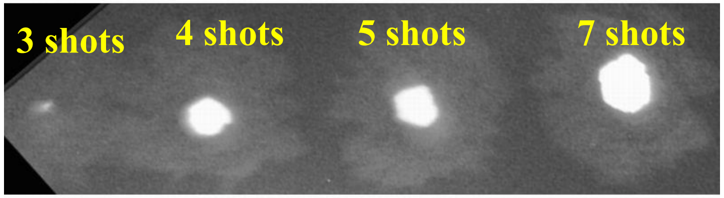
Y. Ueno *et al*. Appl. Phys. Lett. **91**, 231501 (2007).

CO_2 laser-produced Gd plasma at ISAN

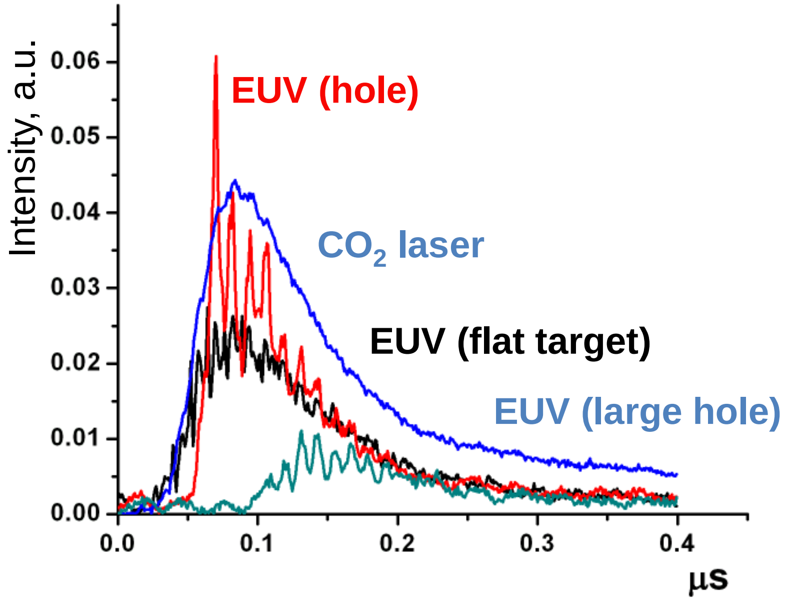


Target – Gd foil 80 μ thick

Laser energy 600 mJ
Laser spot dia. 300 μ
Pulse duration 100 ns
Pow. density ~10^{10} W/cm^2



View of holes in 80 μ Gd foil after defined number of laser shots



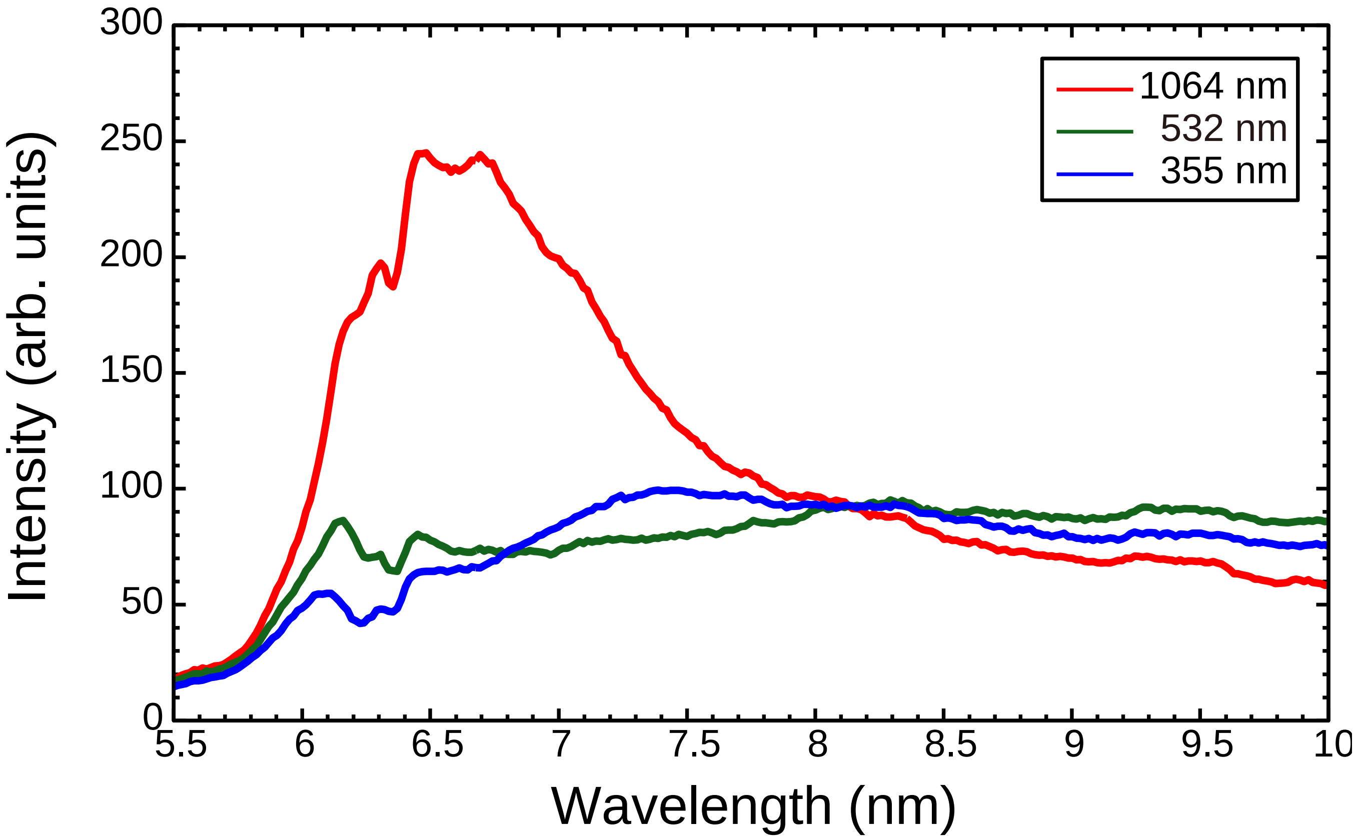
RnD ISAN

CEs are comparable under 2%BW

Gd and Tb have the similar property due to Δn = 0 UTA emission

- Spot diameter: 50 um (FWHM)
- Laser energy: 320 mJ
- Laser intensity: 1.6 x 10^{12} W/cm^2

T. Otsuka *et al*., APL **97**, 111503 (2010).
T. Otsuka *et al*., APL **97**, 231503 (2010).



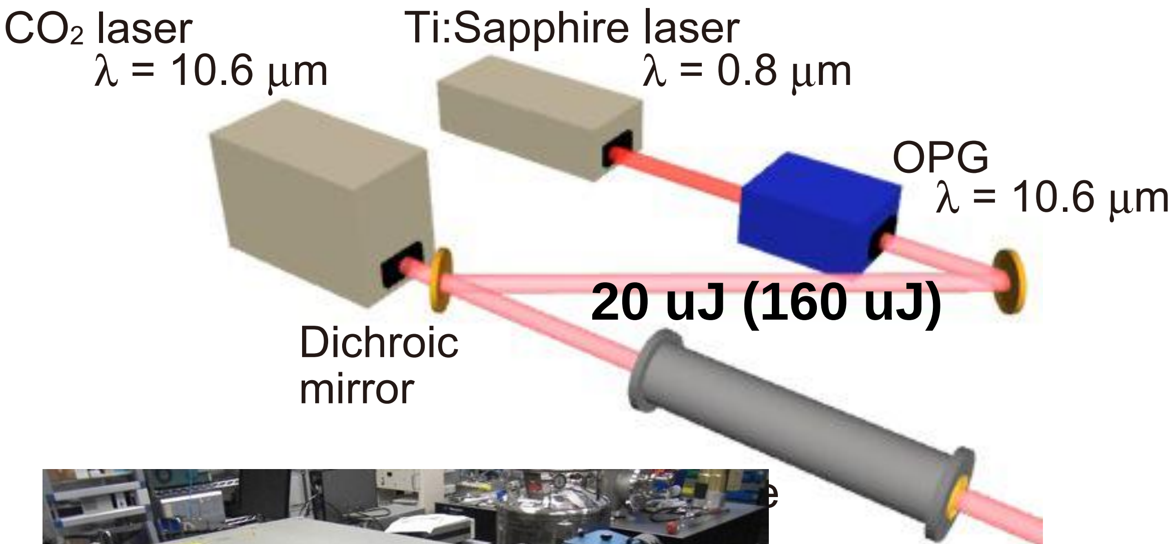
EUV CEs
(in 2% BW)

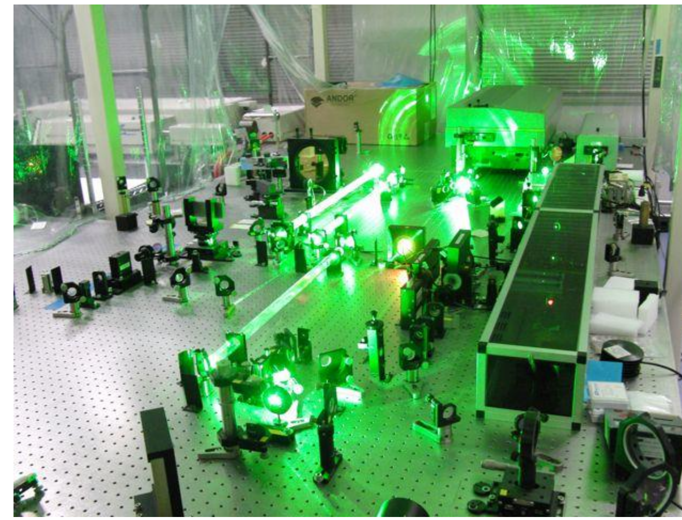
1064 nm: 1.1%

532 nm: 0.7%

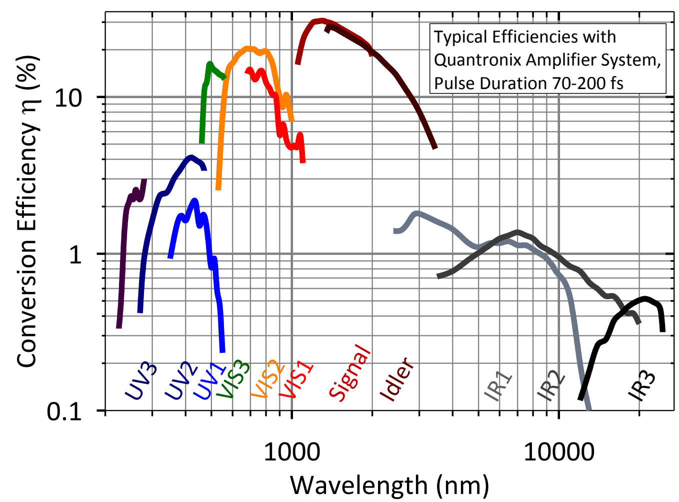
355 nm: 0.5%

Next step: short CO_2 laser installation
sub-ns 10-Hz hybrid 10.6-um laser development





Expected:
160 mJ



Summary fro 6.x-nm BEUV

We have demonstrated the efficient EUV sources

- Numerical evaluation of Gd and Tb (by Li, Kilbane & O'Sullivan)
- Proposal of mixing target for MLM (by O'Gorman & Otsuka)
- P plasma for low-temp plasma (by Cummins & Otsuka)
- Hybrid laser system (by Otsuka, Sakaue, Miura & Endo)

New concept flash WW-SXR source

Our objective is a demonstration of high-brightness, high energy EUV/soft x-ray source in water window (3.2 nm) for the first time in the world!!!

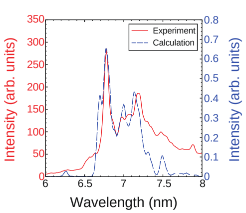
Lithography

EUV & BEUV source study
Wavelength: 13.5 & 6.x nm


半導体 容量10倍へ
回路描く光 微細化成功
宇都宮大など

半導体を使った電子部品の小型化に向け、研究を進めていた宇都宮大（宇都宮市）や長岡技術科学大（新潟県長岡市）などのグループが、半導体に回路を描く光の微細化に成功した。波長が従来の30分の1で、より小さな回路を描くことができる。グループの東口武史・宇都宮大准教授は「実用化すれば同じサイズの電子部品でも容量が10倍以上になる。スマートフォン（多機能携帯電話）でDVDが見られるほど性能が上がり、コストダウンにもつながる」としている。

ろ6・5〜6・7 と、より短い波長の が得られた。幅10 以下の線も描けるとい う。



MEXT

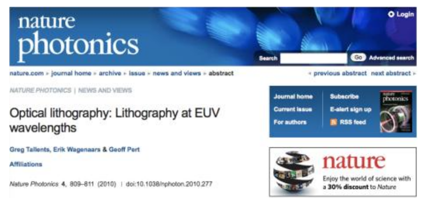
キヤノン財団 The Canon Foundation

NEDO

宇都宮大学 UTSUNOMIYA UNIVERSITY

APL x 7
(2010-2012)

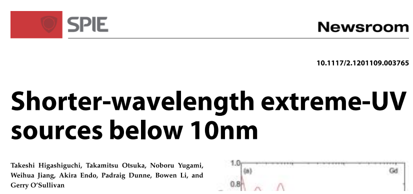
Shorter wavelength


nature photonics

Optical lithography: Lithography at EUV wavelengths

Greg Tallents, Erik Wagenaars & Geoff Pert

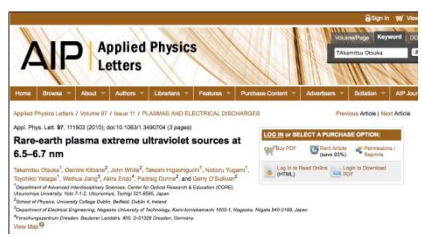
Nature Photonics 4, 809–811 (2010) | doi:10.1038/nphoton.2010.277


SPIE Newsroom

10.1117/2.1201109.003765

Shorter-wavelength extreme-UV sources below 10nm

Takeshi Higashiguchi, Takamitsu Otsuka, Noboru Yugami, Weihua Jiang, Akira Endo, Padraig Dunne, Bowen Li, and Gerry O'Sullivan

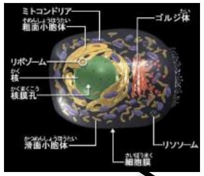

AIP Applied Physics Letters

Rare-earth plasma extreme ultraviolet sources at 6.5–6.7 nm

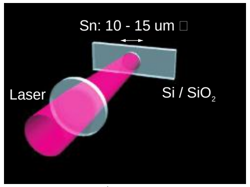
Life Innovation

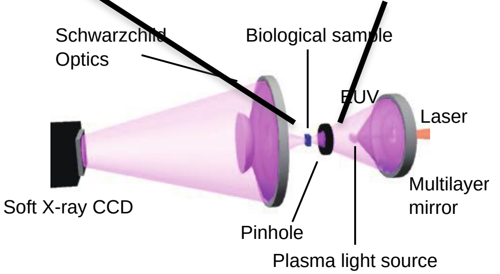
Compact source development for Bio.
Wavelength: 2-4 nm

In vivo cell observation



Original micro source





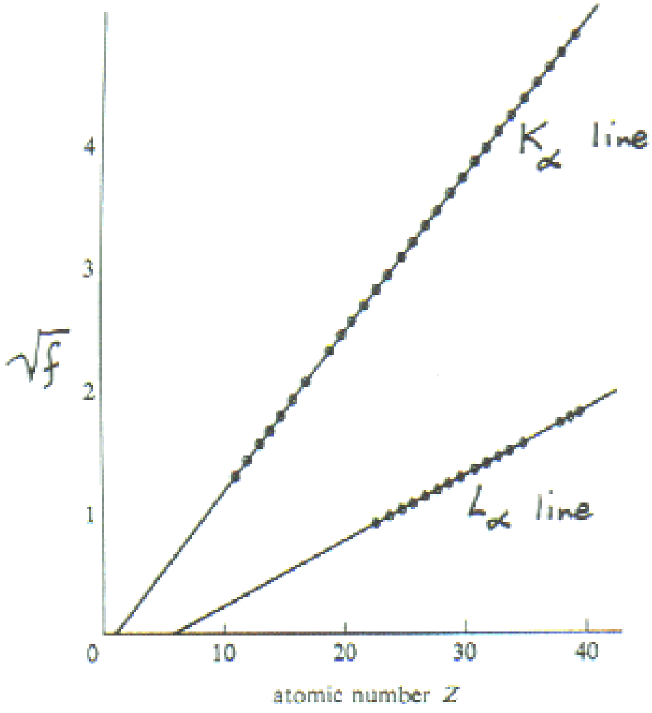
Single shot, flash biological imaging

Proposal (APL x 1)

Moseley's law?

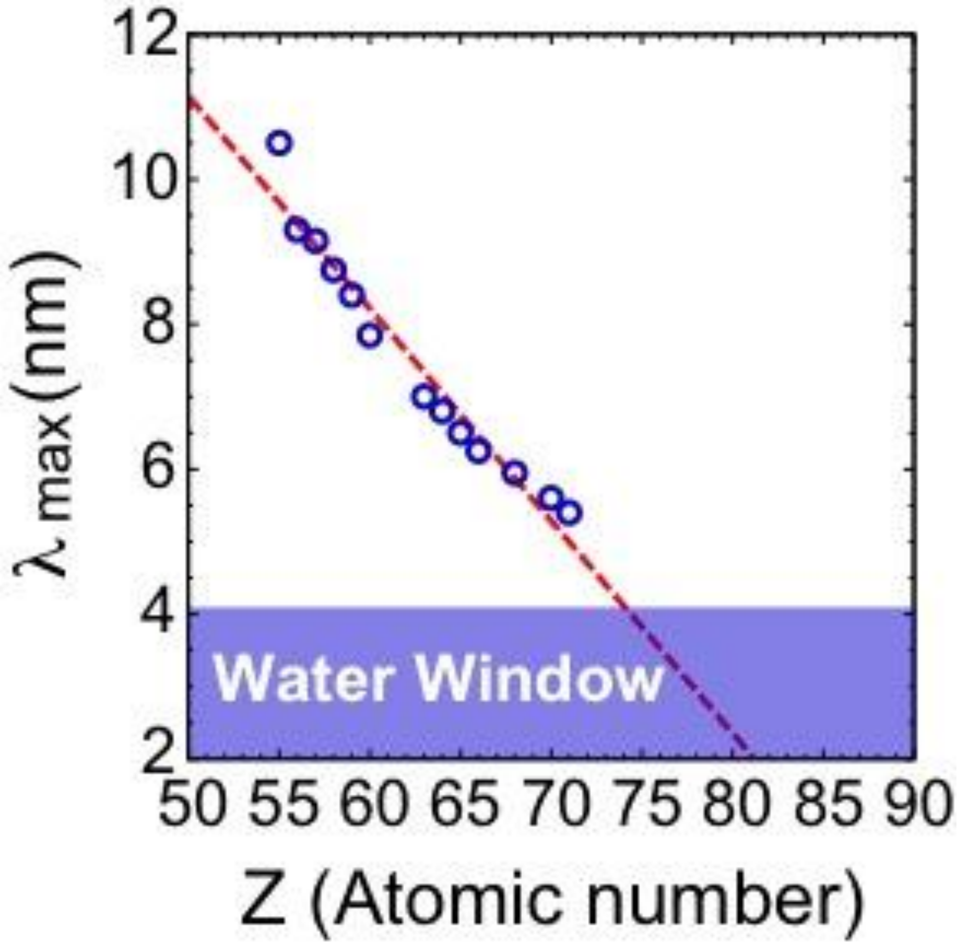
$$\sqrt{f} = k_1 \cdot (Z - k_2)$$

$$\sqrt{E} \propto Z$$



Z scaling: quasi-Moseley's law

by Prof. O'Sullivan and Prof. Endo



Z = 55: Cs

Z = 60: Nd

Z = 64: Gd

Z = 65: Tb

Z = 71: Lu

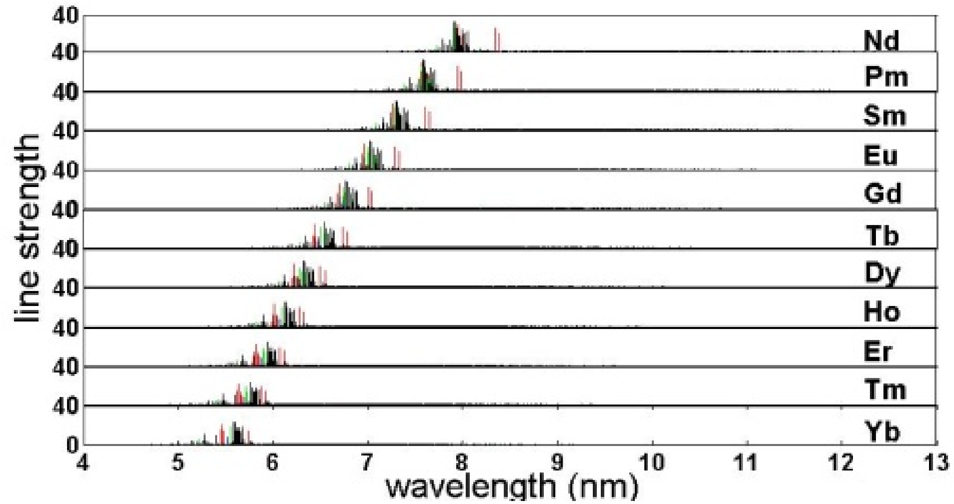
Numerical simulation

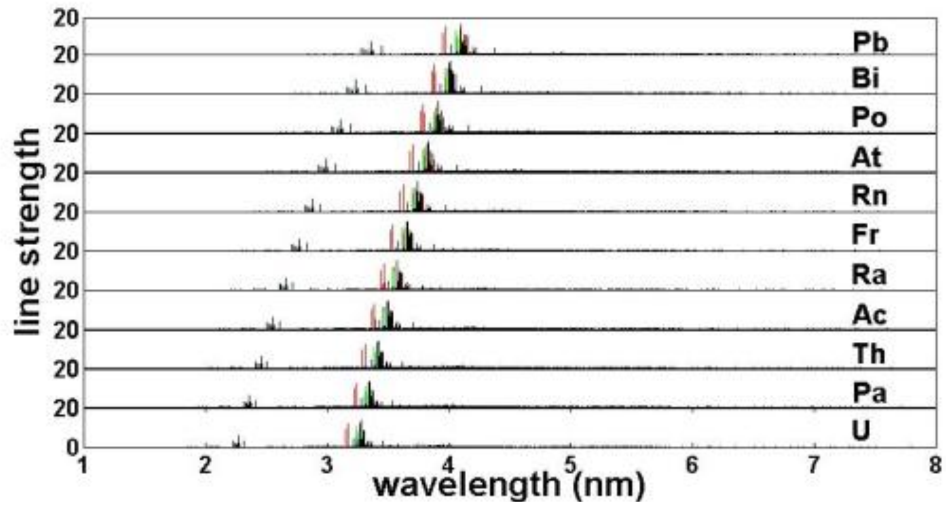
SPIE Newsroom

10.1117/2.1201109.003765

Shorter-wavelength extreme-UV sources below 10nm

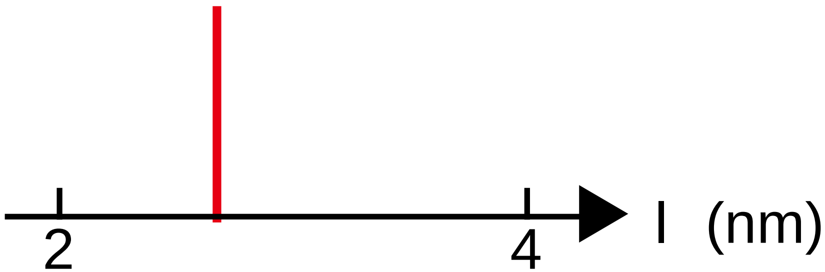
Takeshi Higashiguchi, Takamitsu Otsuka, Noboru Yugami, Weihua Jiang, Akira Endo, Padraig Dunne, Bowen Li, and Gerry O'Sullivan



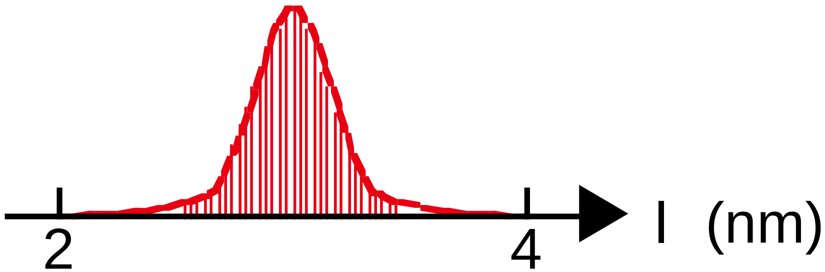


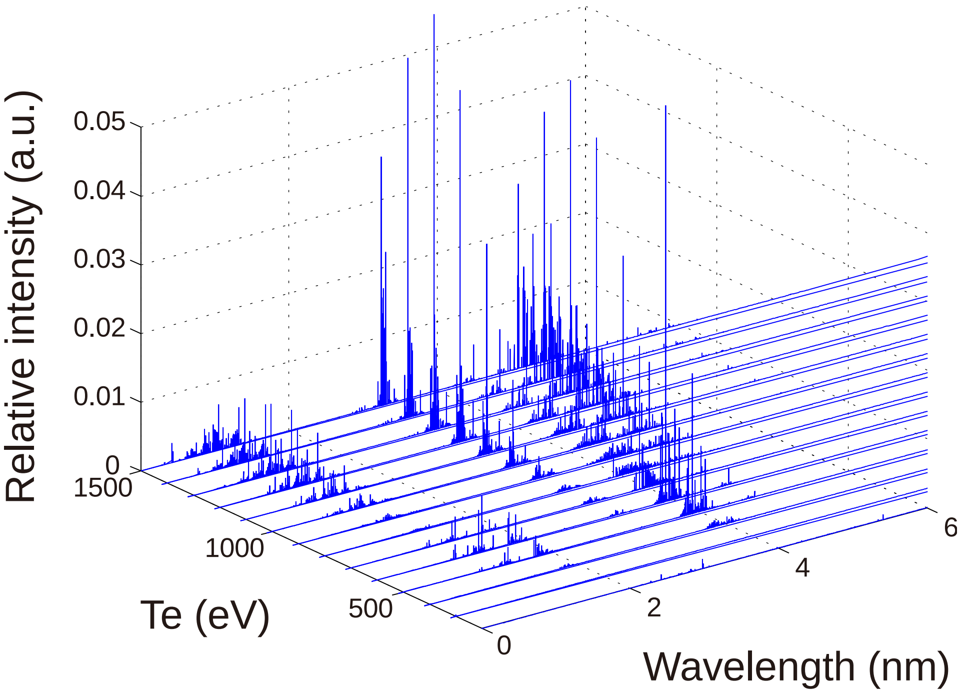
Unresolved transition array (UTA)

(a) Line spectrum



(b) UTA





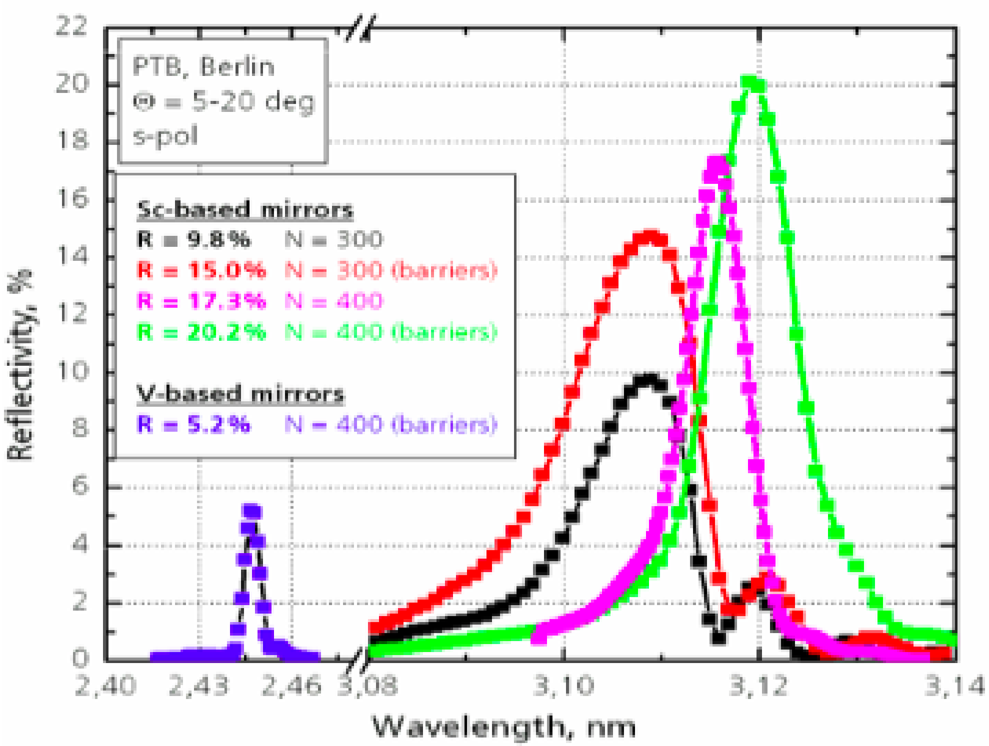
T. Higashiguchi *et al*., Appl. Phys. Lett. **100**, 014103 (2012).

New concept flash source

Fraunhofer IOF

Spectral range from 2 to 5 nm

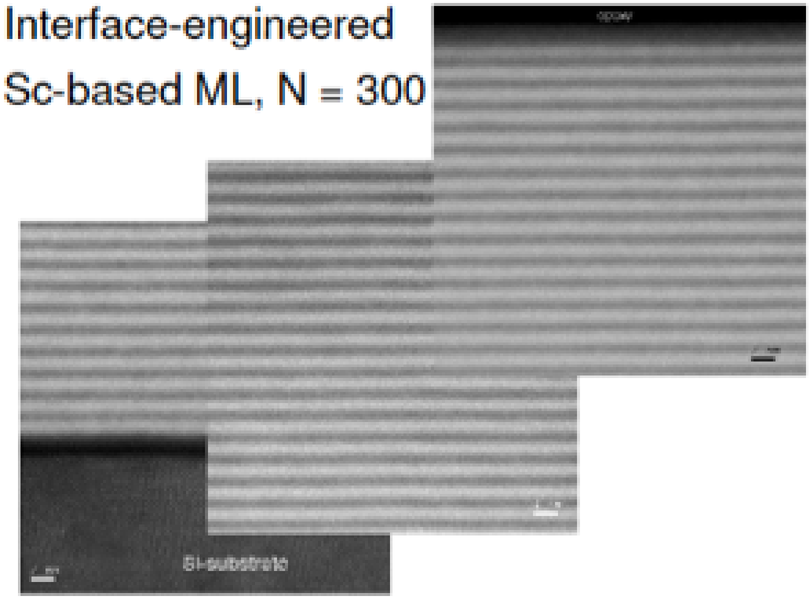
Enhanced reflectance of Sc- and V-based multilayer mirrors with interface-engineering



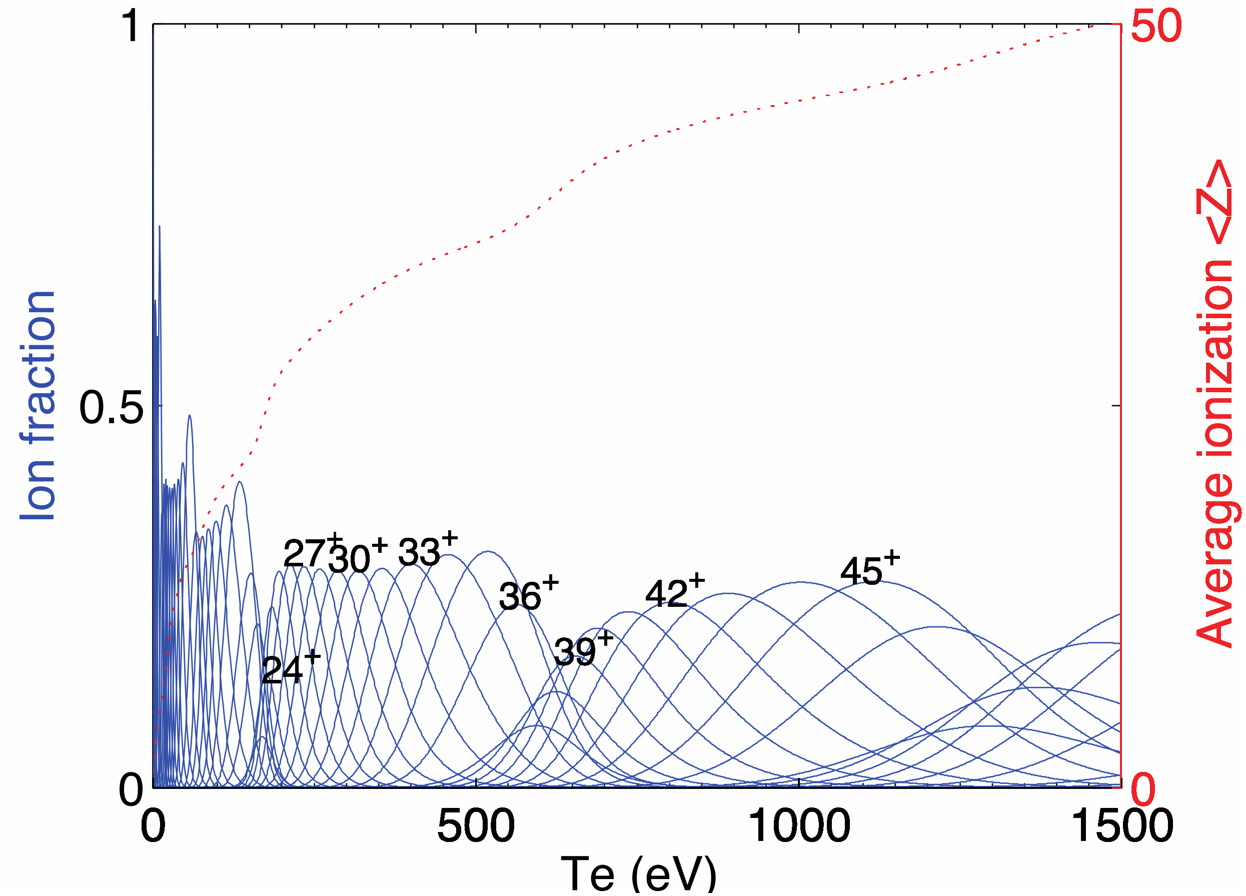
S. Yulin et al., "Hochreflektierende EUV/Röntgen-Mehschichtspiegel", Photonik 2, 2008

Multilayer	λ	N	R	FWHM
Sc - based	4.4 nm 3.1 nm	300 400	7.1 % 20.2 %	0.021 nm 0.008 nm
V - based	2.5 nm	400	5.2 %	0.006 nm

Interface-engineered Sc-based ML, N = 300

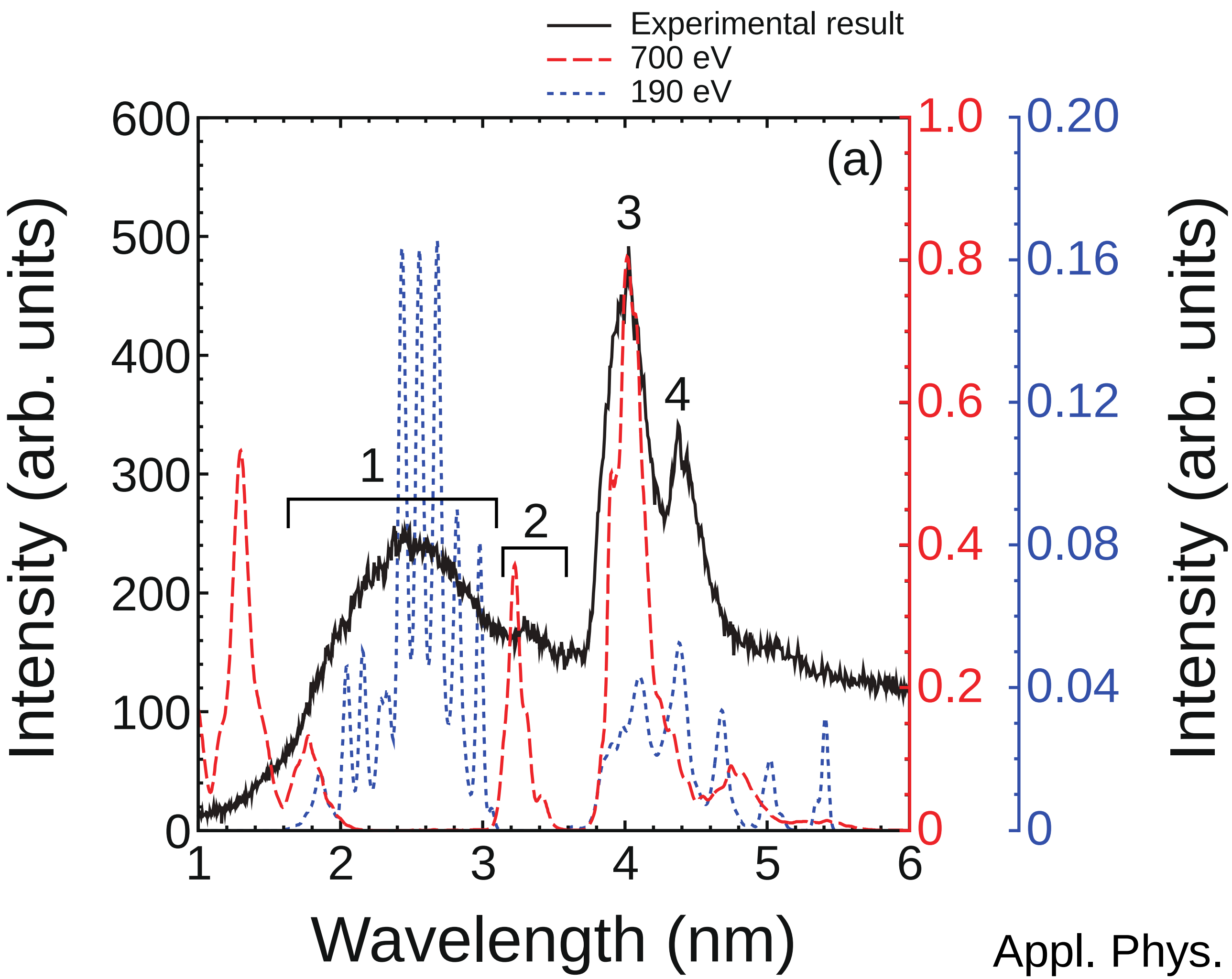


Bi plasma condition



T. Higashiguchi *et al*., Appl. Phys. Lett. **100**, 014103 (2012).

Bi plasma spectral analysis



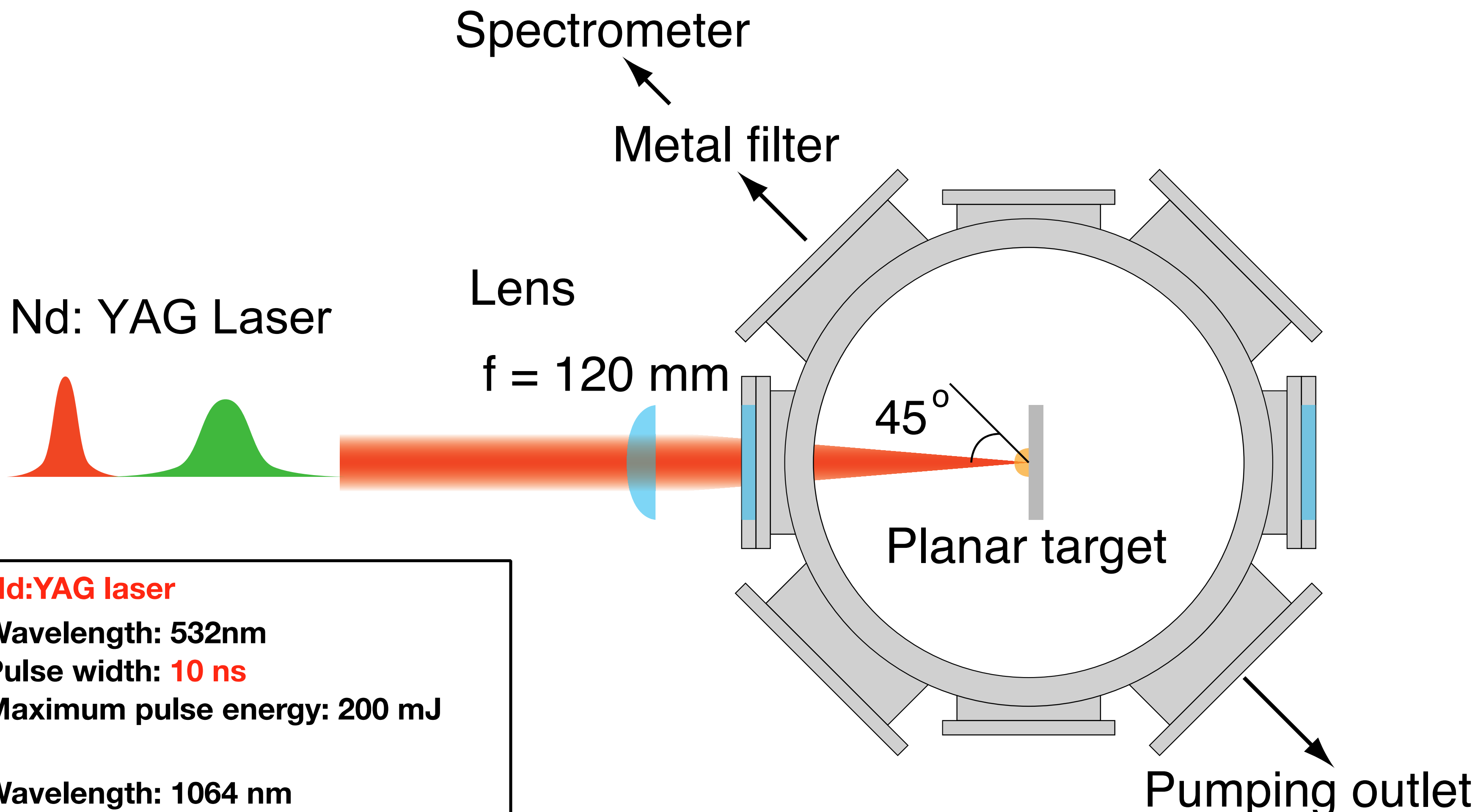
1: 4f-5g, < Bi^{35+}

2,3: 4p-4d, 4d-4f, Bi^{36+}-Bi^{45+}

4: 4d-4f

Appl. Phys. Lett. **100**, 014103 (2012).

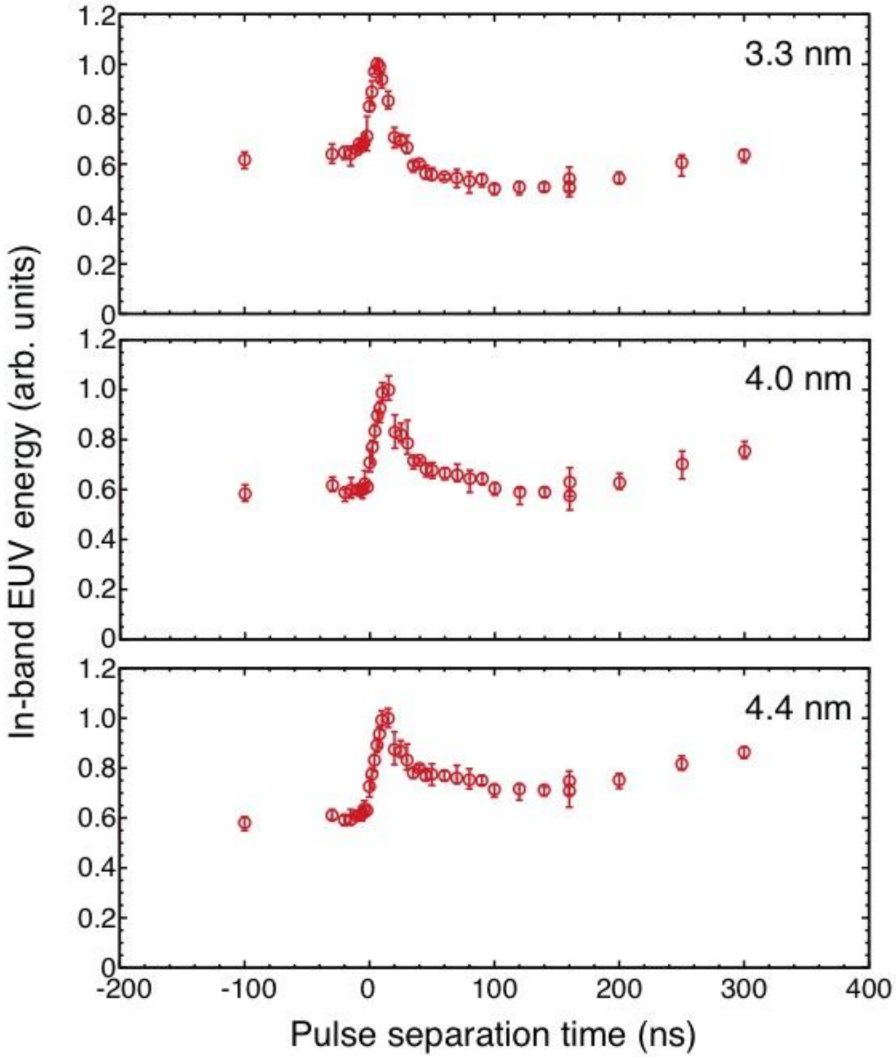
Dual laser pulse Bi plasma

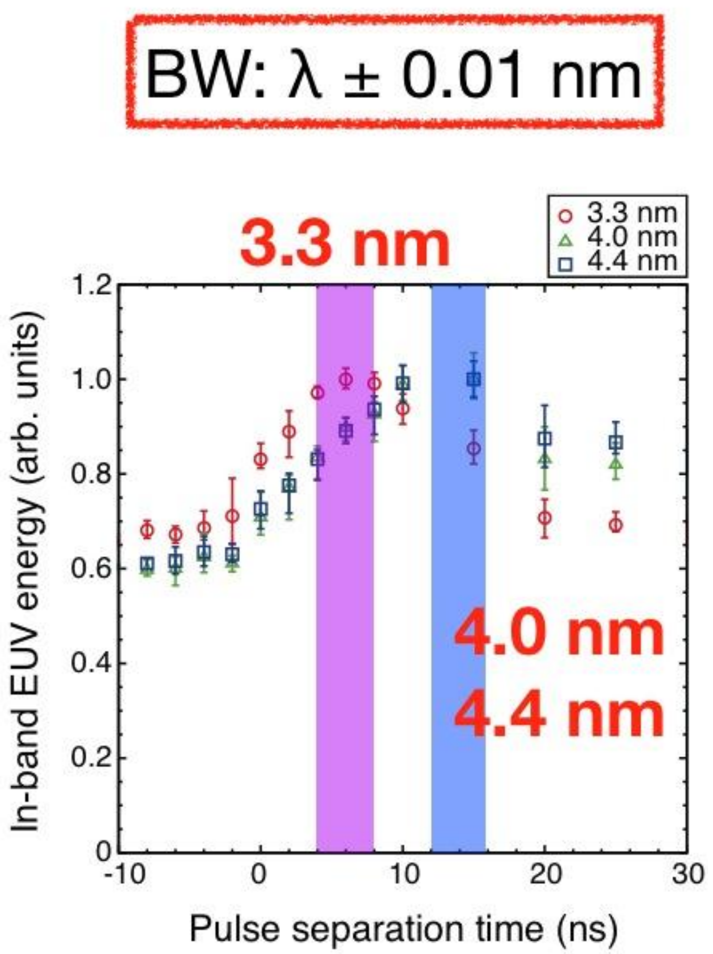


Nd:YAG laser
Wavelength: 532nm
Pulse width: 10 ns
Maximum pulse energy: 200 mJ

Wavelength: 1064 nm
Pulse width: 150 ps
Maximum pulse energy: 220 mJ

Dual laser pulse Bi plasma





Observation of Leydig cell in culture solution

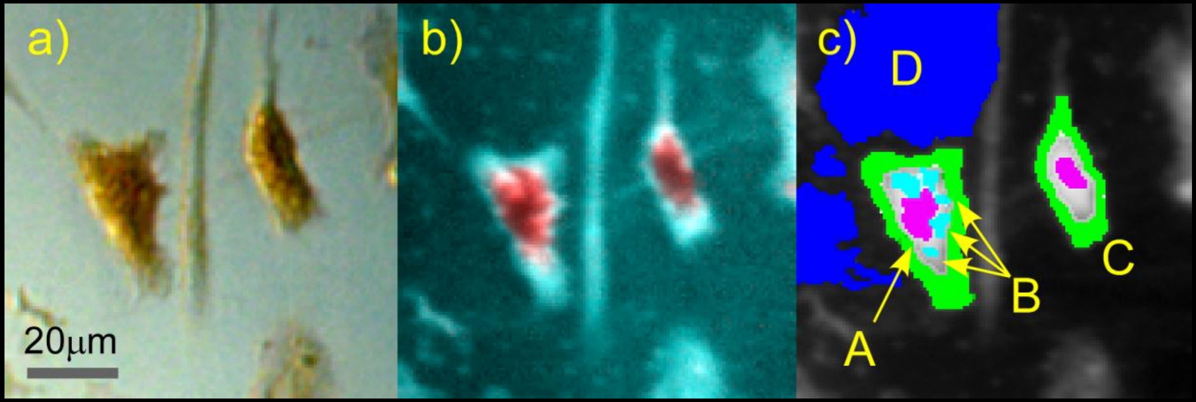
Sample: Cultured on SiN membrane and fixed by formalin solution.

Beam line: Spring-8 BL27SU,

- Photon energy: 260〜600 eV (2.1 〜 4.8 nm),
- Exposure time: 0.8 ~ 180 sec,
- Spatial resolution: 1.1μm,
- Wavelength resolution: $\lambda/\Delta\lambda$ = 2000

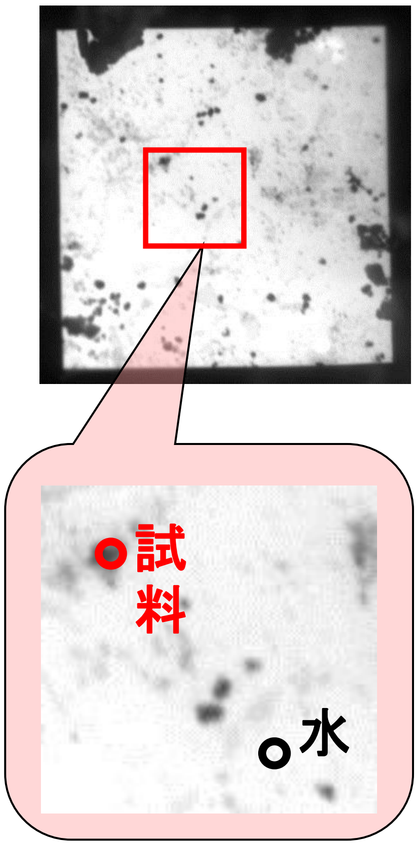
Image comparison:

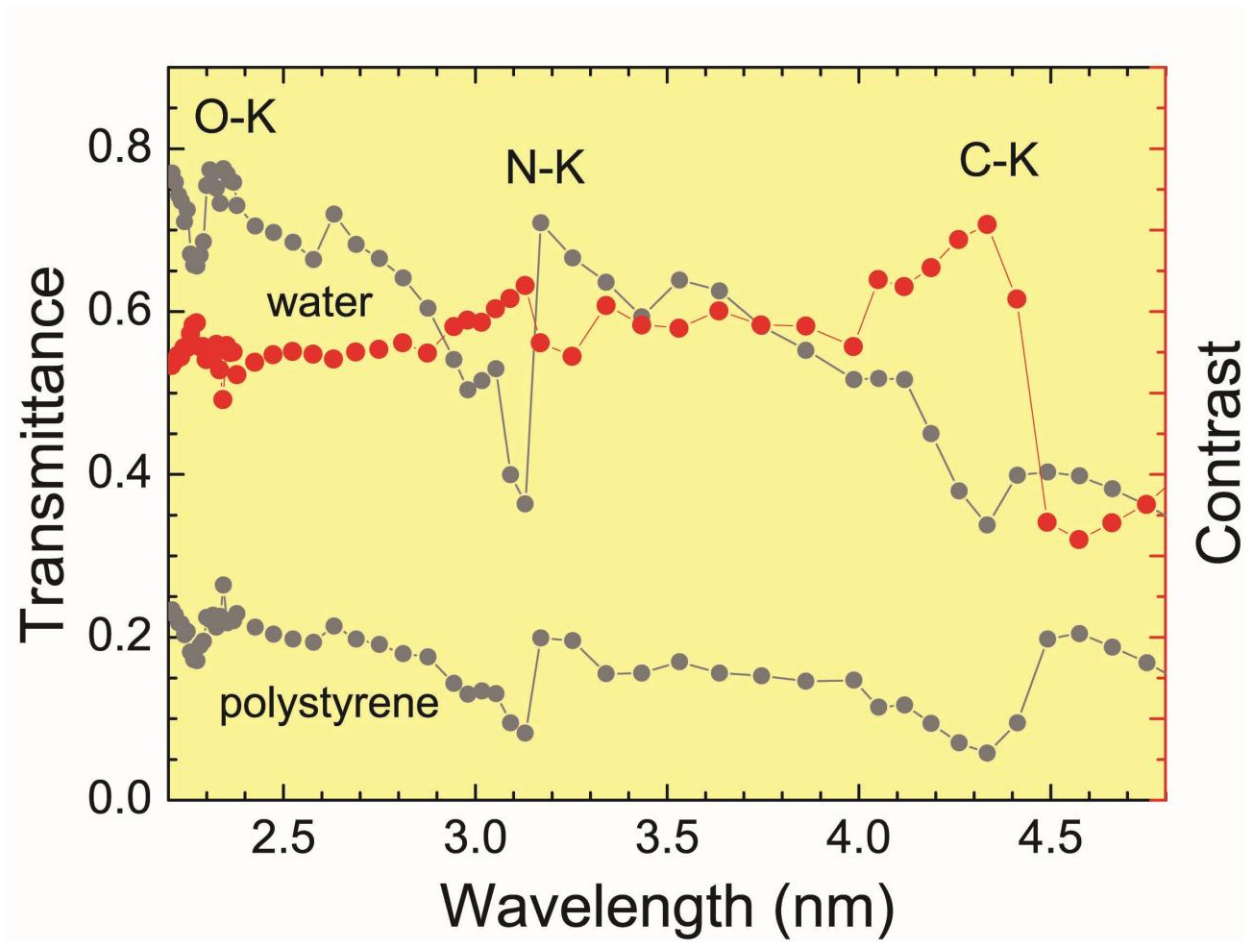
VI diff. int. img. 536eV – 529eV ROI



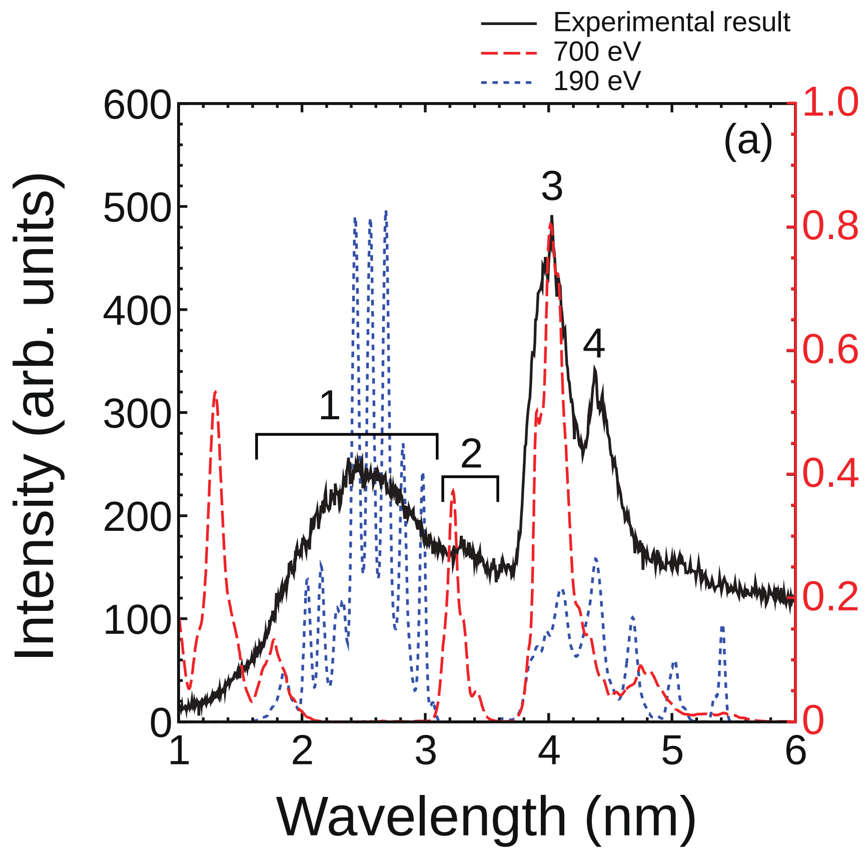
Absorption in a biological sample

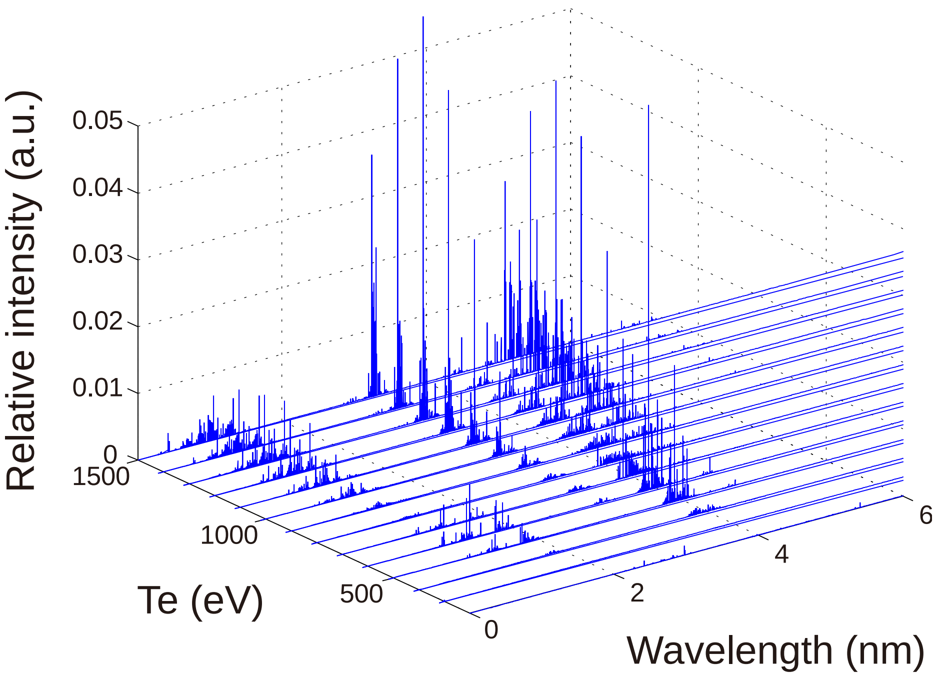
透過率像　2.38nm





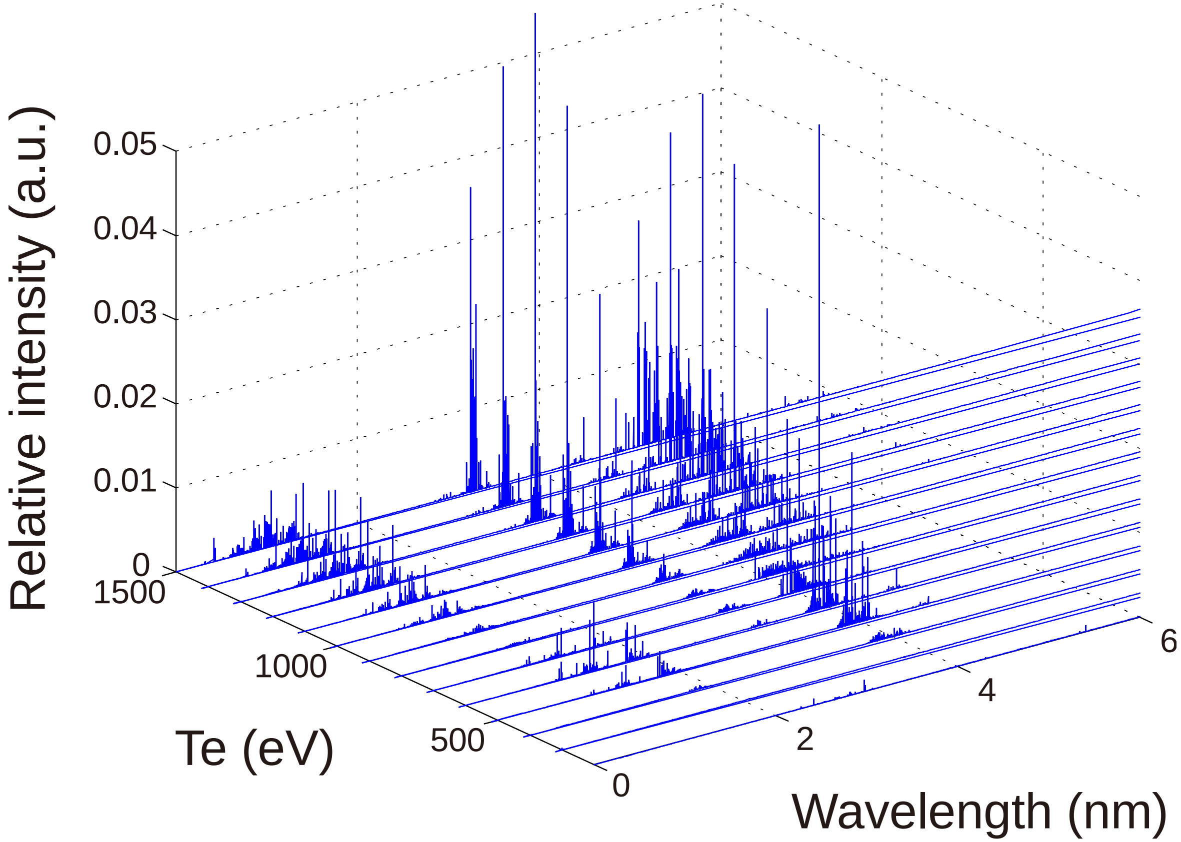
Proposal of two-color WW-SXR source





T. Higashiguchi *et al.*, Appl. Phys. Lett. **100**, 014103 (2012).

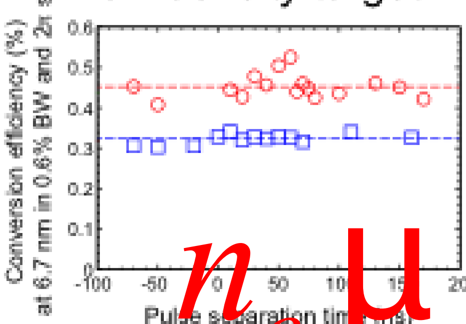
Challenging: 1-keV WW-SXR



T. Higashiguchi *et al*., Appl. Phys. Lett. **100**, 014103 (2012).

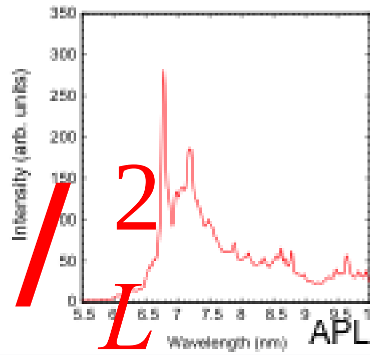
Low density & 100-eV plasmas

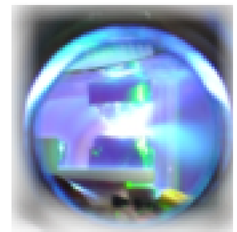
low density target



APL **99**, 191502 (2011).

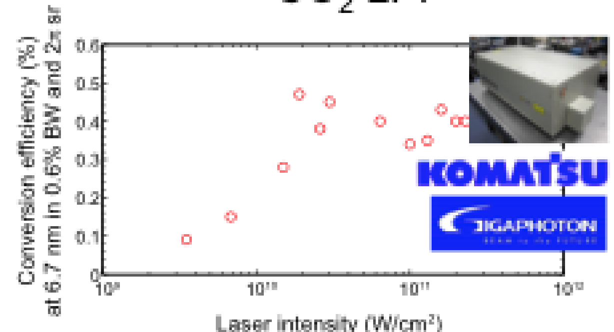
DPP





APL **99**, 231502 (2010).

CO_2 LPP



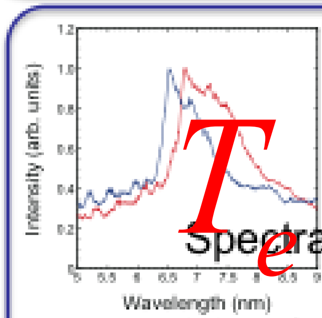
$$n_e \propto 1/\lambda_L^2$$

$$I(\lambda) = I_0(\lambda) e^{-\sigma n \ell}$$

$$T_e \propto (I_L \lambda_L^2)^{1/2} \propto \lambda_L / \sqrt{\tau_L}$$

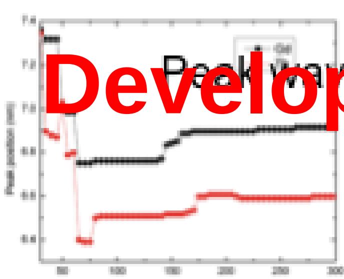
$$\ell \approx c_S \tau_L$$

Spectral structure



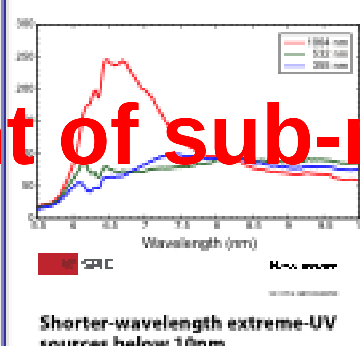
APL **97**, 111503 (2010).

Peak wavelength

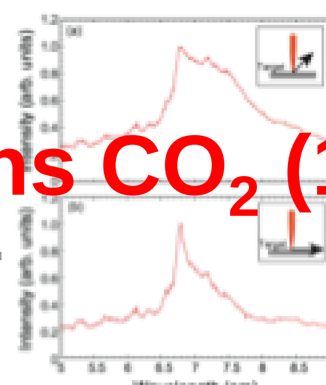


APL **101**, 013112 (2012).

Self-absorption

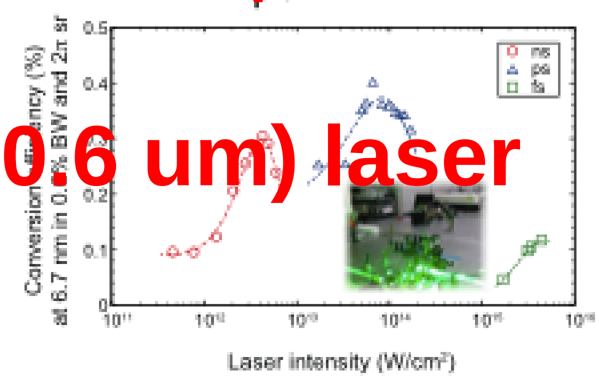


APL **97**, 231503 (2010).



APL **100**, 141108 (2012).

ps LPP

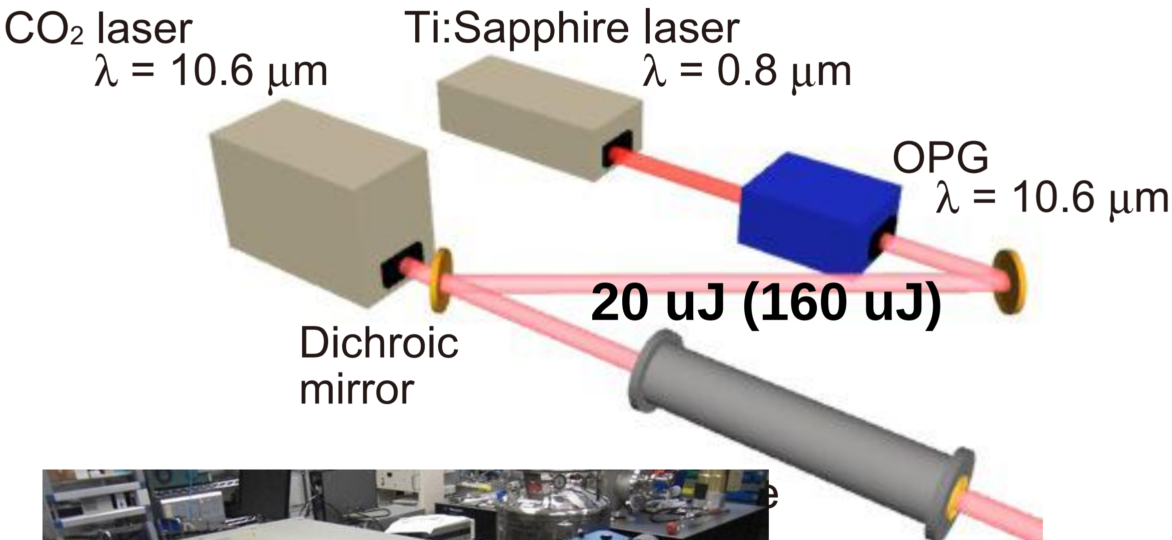


APL **100**, 061118 (2012).

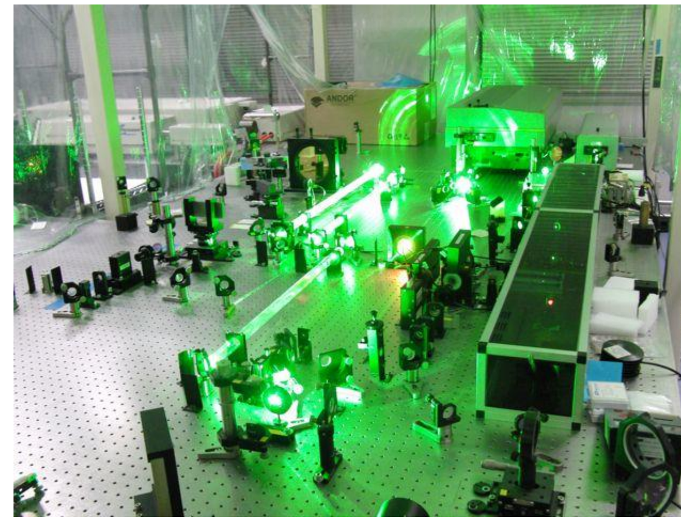
Development of sub-ns CO_2 (10.6 um) laser

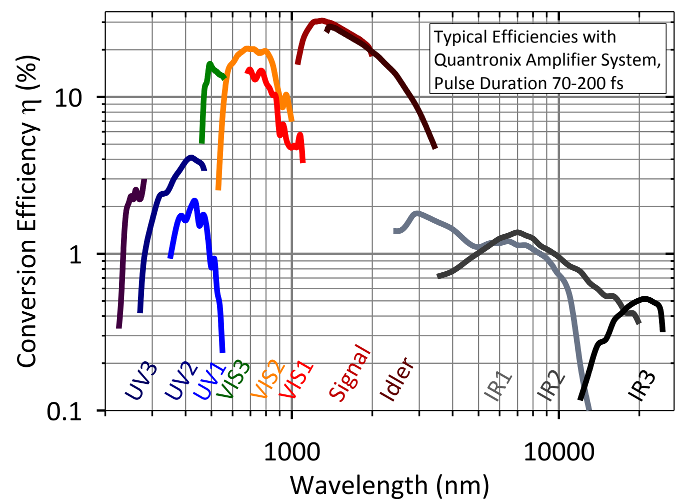
Next step: short CO_2 laser installation

sub-ns 10-Hz hybrid 10.6-um laser development

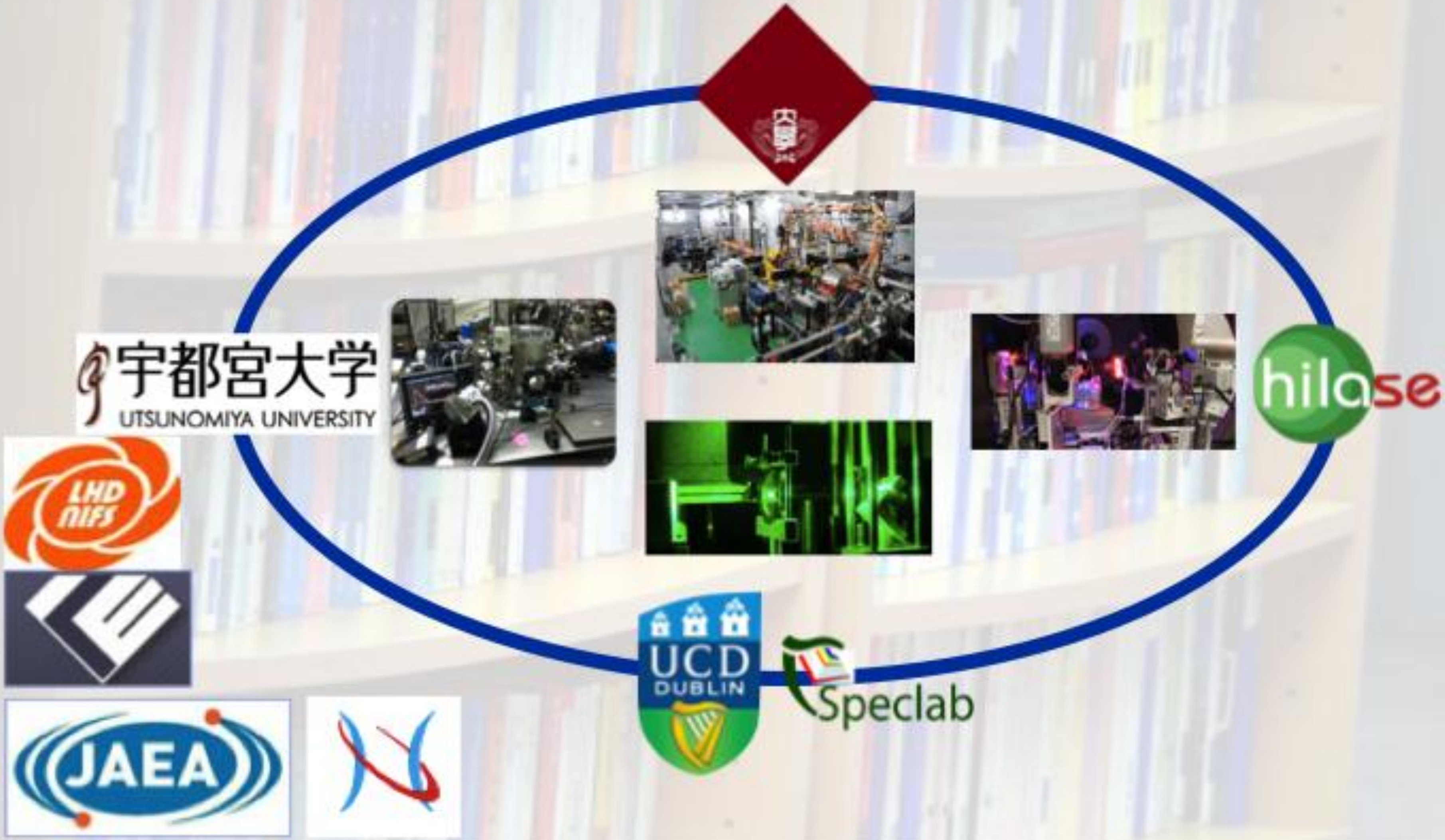


Expected:
160 mJ





Future for more HW: collaboration



Summary

We have shown the wavelength scaling and various property of BEUV & SXR by UTA emission concept.

Thanks a million!!!

宇都宮大学
UTSUNOMIYA UNIVERSITY

JST

GIGAPHOTON
BEAM to the FUTURE

KOMATSU

UCD DUBLIN

sfi Science Foundation Ireland

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